Reply to Reviewers

We thank the two reviewers for their constructive comments and suggestions, which have further improved the quality of our manuscript considerably. Their comments are reproduced below with our responses in blue. The corresponding edits in the manuscript are highlighted with tracked changes. The line numbers are based on the revised manuscript.

Reviewer #1:
This paper provides a unique method for taking advantage of ozone lidar data for evaluating models. This could be a valuable contribution and appropriate for ACP, however the description of this method and the model evaluation need major revision. As presented, the model evaluation using lidar data does not suggest anything to improve about the models other than increased resolution. Overall, the paper is lacking in explanations for the model failures in representing the five ozone clusters. If model resolution is the only clear factor, the authors should apply their method to regional, high-resolution modeling done for LISTOS (see comments below) at least. The model evaluation also does not provide much insight into how the clustering method is superior to a simple average comparison of model vs. observations. This study would be significantly strengthened by clear examples of how their clustering example provides specific insights over a simple average comparison. The authors could also better describe the benefits of lidar data beyond other types of profiles (e.g. ozone sondes, aircraft profiles) and show specific examples of these benefits.

Major comments.

Clustering algorithm
The k-means clustering algorithm needs better explanation. Did the authors choose the 8 features and then confirm they best represented the data with k-means? Did they try different numbers of features? What was the rational for looking at the data in this way? What about day-to-day variability, driven by different synoptic? I do not understand how the clustering algorithm was applied to the eight features. The authors might consider a diagram that shows how the 8 features lead to the 5 clusters.
Response: We described the choosing and evaluation of the features for cluster tendency in lines 189 – 197. Following the reviewer's suggestion, we have further elaborated on the description of input features in the Supplementary Material Text S1. Clustering algorithm and efficacy tests are described in Text S2. Figure S2, S3, and S4 were added to help illustrate the clustering method.

One of the main factors that led the choosing of the features was the actual structure of the lidar measurements as described in Section 2.2.1. We had to work within the limitations of the lidar measurements e.g., the time of day they lidar instrument was operating and the processing of the data that can limit the data that is available as well as the accuracy of the data. We also had the goal to evaluate lower-level tropospheric ozone which is also why we limited the entire vertical profile to 4000 meters.

We chose the two altitude subsets based on the structure of the vertical atmosphere. One way we could have explored different input features would be to choose features that followed the development of the boundary layer more precisely. Since a more in-depth evaluation of the development of the boundary layer would be needed to do this, we concluded that it was out of the scope of this work. Therefore, we chose the altitude subset 0 – 2000 meter to represent the complete evolution of the boundary layer, while the 2000 – 4000 meter subset represents the part of the vertical profile in which other factors such as longer range transport of pollutants would be of greater influence. We chose the 4 subsets of time following the common diurnal pattern of pollutant behavior. Tropospheric ozone has a common diurnal pattern that is greatly influenced by the presence of sunlight. The first subset of time (F1, F5) represents the early morning before the sunlight has reacted with precursor pollutants to create tropospheric ozone. The second time subset (F2, F6) represents the time of day in which the sun rising, and morning traffic have begun which both have an influence on ozone chemical reactions. The third subset of time (F3, F7) represents the midday time in which the sun is at its' full peak. At this time of the day tropospheric ozone usually peaks and remains at the maximum concentration of the day. The final time subset (F4, F8) represents the evening time in which the sun has/begun to set, and ozone concentrations decrease. As explained in line 167, we rationally chose these features to best represent the structure of the lidar measurements and to best represent the behavior of O_3 vertically and temporarily. With the goal of clustering most efficiently, this is in part to simply the data so that the results of the clusters are not weakened by too many input features. But also, not oversimplify the data so that we lose the details of the lidar data.

Analysis

In the discussion of modeled vs. observed meteorology, key findings should be discussed, not 'slight differences'. The readers are interested in what your model/observational comparison reveals about missing model processes that would be important to simulating surface ozone, particularly exceedances. Focus on highlighting those results and remove discussion about minor features.

Response: We agree with the reviewer's comment and have altered the manuscript to remove slight differences and to solely focus on larger discrepancies. See updated Section 3.3.1. We thank the reviewer for their constructive comment as the quality of the manuscript has been substantially improved.

Model selection

As the authors conclusion is that neither model has sufficient resolution to capture the sea breeze, this study would greatly benefit from including the regional modeling done for LISTOS (and possibly OWLETS?). WRF-Chem modeling was done for LISTOS. I suggest contacting NESCAUM to ask for this output.

Response: We have taken the reviewer's suggestion into consideration but have ultimately concluded that we will not be able to add a regional model analysis to the manuscript. The main purpose of this manuscript is NOT to evaluate specific model performances against LISTOS and OWLETS observations. Instead, our goal was to emphasize the value of the developed clustering method as an efficient way of comparing a suite of lidar observations with models. Also, the purpose of the manuscript is not to completely resolve specific model performance gaps but rather to highlight how the multi-dimensional lidar and cluster approach can help identify the model gaps more readily and provide more in-depth model insight. Per the reviewer's comments on providing a more comprehensive and detailed analysis of why this clustering approach can be more useful than a simpler method, we have better tailored the purpose of the updated manuscript – see changes made in Section 3.3. Although a regional modeling analysis is out of the scope of the current manuscript, we added in the conclusion section that using multi-dimensional lidar measurements to evaluate regional modeling (such as WRF-Chem) will be in our future work (Lines 696 -697).

Minor comments.

Line 58 – You say "set out to address this issue" twice.
Response: Thank you, we corrected this. Line 57.

Line 165 – Could you please further explain this sentence "Input features (seed values) were rationally established…"
Response: We have further elaborated on the input feature selection in the Supplementary Material Text S1- Description of input features. As well as the clustering algorithm in Text S2.

Line 223 – Can you describe whether using the 40 complete profiles before data-filling was performed would give similar results? It seems somewhat problematic to fill the data based on observed patterns and then cluster the results also on observed patterns. Giving a little more information on why this approach is valid would be useful.
Response: We understand the reviewer's concern, and we have provided more clarification. This was mentioned in line 226: "The silhouette method was used to test the quality of the newly imputed dataset and proved to be no worse, nor better, than the CCA (*real data*) results."

We did test the cluster quality of the 40 complete profiles versus the imputed dataset. The 40 complete profiles did not reveal to have a better quality of clusters than the imputed dataset. Imputation is a common method that has been used for missing data before the clustering analysis. The single imputation technique provides weighted averages of values of the neighbors which is an accurate description of ozone spatially and temporally. An example: a case in which at 13:00 LT there is measured high ozone yet at the next time step there is absolutely no ozone is not common. The imputation was also applied to already averaged data. Therefore, the averaged data might be more representative of the case. We also acknowledged that using an imputation method will possibly introduce bias, but that bias is arduous to quantify. In testing the quality of the CCA dataset, we found that the significance of the clusters was no higher than that of the imputed dataset. Also, if we use the CCA dataset, we are eliminating over half of the curtain profiles with only 40 profiles of full data to use. We could argue that only using half the dataset to characterize coastal ozone during these campaigns introduces an equal or greater bias than imputing the individual curtain profiles to have a full dataset to work with. We therefore concluded to use the imputed dataset so that we could utilize all the full lidar profiles.

Line 288 – By temporal variation, do you mean diurnal variation?
Response: Yes. Line 295 changed to "diurnal variations" for clarification.

Line 299 – Discuss Fig. 3a first or switch the order of the panels in Fig. 3.
Response: The figure is initially discussed in totality to describe the differences of the clusters beginning at Line 294. We have updated the next line to more clearly mention Figure 3a first.

Line 295 – 297: Figure 3a quantifies the between-cluster differences. We separate the data by the two altitude subsets (low and mid-level) and by two time subsets (morning = 6:00 – 12:00 and afternoon = 12:00 – 21:00) for lucidity as the majority of the cluster differences are contrasted between these subsets.

The next paragraph describes the cluster differences more in depth but in order of cluster number.

Fig. 3a – It would be more informative to separate the profiles with altitude into day and night, or 12pm vs. 6am. Fig. 4 shows how the observations and models are both better mixed between roughly 12-16 EDT than during other hours.
Response: This is a good point as the profiles are very different in the morning hours versus afternoon. We have updated Figure 3a (below).

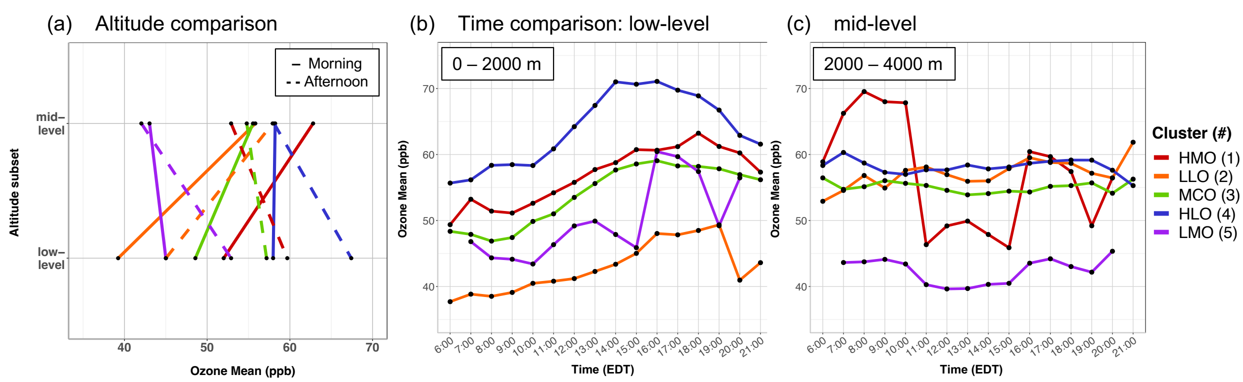


Figure 3. Lidar O_3 cluster average comparisons (five clusters depicted in colors). a) Altitude comparison of mean O_3 averaged over time: morning hours from 6:00 – 12:00 (solid line) and afternoon hours from 12:00 – 21:00 (dashed lines). Time comparison of mean hourly O_3 split between the b) low-level and c) mid-level.

Line 310 – Can you examine each of the 5 curtains and tell us for sure whether this is the reason? Or you could provide a standard deviation version of Figure 4 that would help us understand the cluster variability.
Response: This line in the manuscript has been changed to better describe Cluster 5's low-level uniqueness.

Line 318-320: "Cluster 5 does not have a smooth-evolving O_3 diurnal pattern in the lower level (Figure 3b), which can be attributed to the averaging of only five different profile curtains that were assigned to this cluster (Table 1).

We cannot say that Cluster 5 merely has the most variable low-level O_3 since it actually has a slightly lower standard deviation than Cluster 4. This is because Cluster 4 has the highest evening O_3 and compared to the rest of the diurnal pattern such as the early morning O_3, this is the most variable. By making changes to lines 318-320 to better indicate the description of Cluster 5 and since standard deviation statistics do not bring any new information that cannot be derived from Figure 4 already, we have decided to leave the figure as is without adding the standard deviations.

Line 319 – Give the cluster definitions earlier in the text before the introduction of Table 1.
Response: We understand the reviewer's suggestion, but since the cluster nomenclature are derived based on the paragraphs before this (i.e., the entire descriptions of the different clusters), we do not think that the cluster definitions can be introduced before Table 1. Even so, the information that is provided in Table 1 (e.g., Table 1a – No. of vertical profiles) is also used in the naming of the clusters. To remove the confusion, we have eliminated the nomenclature of the clusters from Table 1 and have just left the cluster numbers.

Line 329 – Are the clusters spread across the three campaigns? Describe how each campaign contributes to each cluster.
Response: Yes, the different campaigns are spread throughout the clusters. The different campaigns do not contribute uniquely to any cluster.

Table 1 – Consider including Tmin and Tmax, and WSmin and WSmax. They could just be in parenthesis instead of separate columns.
Response: Done.
We have updated Table 1:

Cluster #	**a) No. of vertical profiles**	**b) O_3 Max** (ppb)	**c) O_3 Min** (ppb)	**d) T avg.** (min; max) (°F)	**e) WS avg.** (min; max) (m s^{-1})
1	25	86.5	42.2	74.1 (67.8; 86.4)	1.5 (0.5; 2.8)
2	14	72.8	28.9	71.6 (64.0; 83.9)	1.6 (0.6; 2.9)
3	28	86.6	34.2	77.2 (67.0; 87.6)	1.3 (0.5; 2.4)
4	18	97.8	44.1	78.4 (68.0; 90.4)	1.2 (0.4; 2.3)
5	5	67.7	29.1	74.5 (66.8; 74.5)	1.2 (0.3; 3.4)

Line 330 – What do you mean by "...could demonstrate background O3 in the case studies"?
Response: The clustering analysis captures an associated trend of background O_3 (Cluster 4 – HLO), which reveals the profile begins with the highest averaged ozone. For HLO cluster the higher O_3 present in the mid-level also translates to the higher O_3 found in the low-level near the surface. This could mean that this higher O_3 already present in the early hours may not be a part of the local production of O_3. This could be helpful in other analyses looking for cases of background O_3 versus locally produced O_3 cases. I clarified this statement in the manuscript for further understanding. Updates below.

Line 339 - 345: Figure 3b and 3c indicate each cluster represents a different O_3 evolution pattern, likely related to different photochemical or transport regimes. This kind of evaluation is useful in that it combines O_3 information from both temporal and vertical dimensions. For example, the HLO cluster reveals the specific case in which higher O_3 is captured early in the temporal profile in the low-level and translates to the higher O_3 captured in the low-level as well. The profile curtains show higher background O_3, indicating these cases did not have "clean air" to begin with which can allow a greater accumulation in the low-level in the afternoon. This is an example of how this type of clustering analysis, if applied, could demonstrate background O_3 in the similar case studies.

Line 373 – When you show comparisons to the lidar data for GEOS-CF, are you only including lidar data clusters from OWLETS 2 & LISTOS?
Response: Yes, the quantified biases are only based on OWLETS-2 and LISTOS lidar data for GEOS-CF. But referring to Figure 4a, the mean lidar curtain profiles in comparison with the models, includes the average cluster profiles from all campaigns, so it includes OWLETS-1 as well.

Section 3.3.1 - The authors should use surface ozone monitors to determine whether ozone exceedances of the NAAQS occurred during any of the clusters. This would provide greater weight to the analysis of poor model performance for a given cluster.
Response: This is a great suggestion. The exceedance analysis is added to the manuscript.
Lines 385 – 388: There was only one occurrence during the dates in which the lidar instruments were operating in which there was a recorded maximum daily 8-hour average (MDA8) O_3 exceedance (> 70 ppbv). This exceedance date is 25 May 2018 in which 3 AQS sites in the LISTOS region measured MDA8 O_3 of 73, 72, and 72 ppbv. This curtain profile was assigned to the HMO cluster (Cluster 1), the cluster with high O_3 in the mid-level and moderate O_3 in the low-level and near the surface.

Line 381 – The statement "In Figure 6, we first evaluate the overall relationship and correlation between both models and the lidar data, disregarding the specific clusters" is confusing as Fig. 6 is split into the 5 specific clusters.
Response: This is a typo. Figures 6 and 7 were accidentally switched and have been fixed. Additionally, the correct Figure 6 has been moved to the Supplementary Material as Figure S7 and the original Figure S4 has been moved to the manuscript as Figure 7.

Line 410 - 412: We first evaluate overall correlation and biases between the model and lidar data. The overall correlation between both models and the lidar data, disregarding the specific clusters, based on the two altitude subsets as the performances differ between low-level and mid-level for both GEOS-Chem (Figure S7a) and GEOS-CF (Figure S7b).

Figure 6 – By "Spatial O3 difference", are you just referring to the differences in the vertical and in the diurnal cycle?
Response: Yes. The spatial O_3 difference between the full mean profile curtain of the model and the lidar observations.

Line 404 – Are the lidar observations averaged to the model vertical (and temporal) resolution?
Response: The lidar observations are interpolated to the resolution of the model in Figure 6.

Line 427 – Is this a typo, do you mean "positive percent biases at 13.9, 18.9, and 19.7 %" instead of "positive percent biases at 0.139, 0.189, and 0.197 %? The other bias % values also look like they might be decimal values that need a 100 multiplier.
Response: The reviewer is correct, this is a typo.

Per the reviewer's suggestion (for Line 621) subsequently to calculate the biases with normalized data not absolute data, we have update Table S1 again (see comment and changes further later in the reviewer's comments).

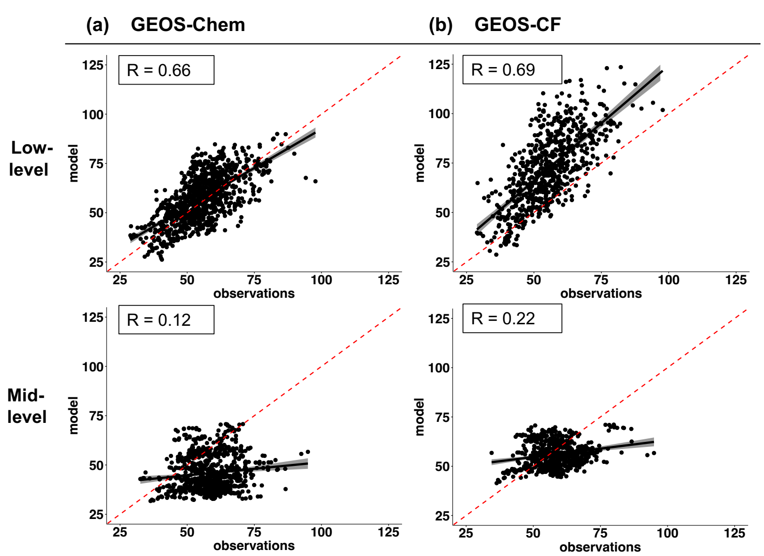
Line 448 – You state "Using the clustering, we are able evaluate how the cluster specific differences reveal additional model performance insight that would be conceivably overlooked when evaluating overall performance." Please give actual examples of how clustering is better than just "to simply group data by altitude to achieve a summarized model evaluation." A clear description of the benefits of clustering over the approach would greatly improve this discussion.
Response: We have updated the analysis in Section 3.3.2 to include a more in-depth analysis of the model performance insight that is only perceivable through the cluster-by-cluster differences.

Line 464 – Does the model overestimate ozone on the first day of these multi-day events?
Response: Correct, the model overestimates ozone on the first day as well but the model also overestimates ozone the rest of the days during the multi-day events.

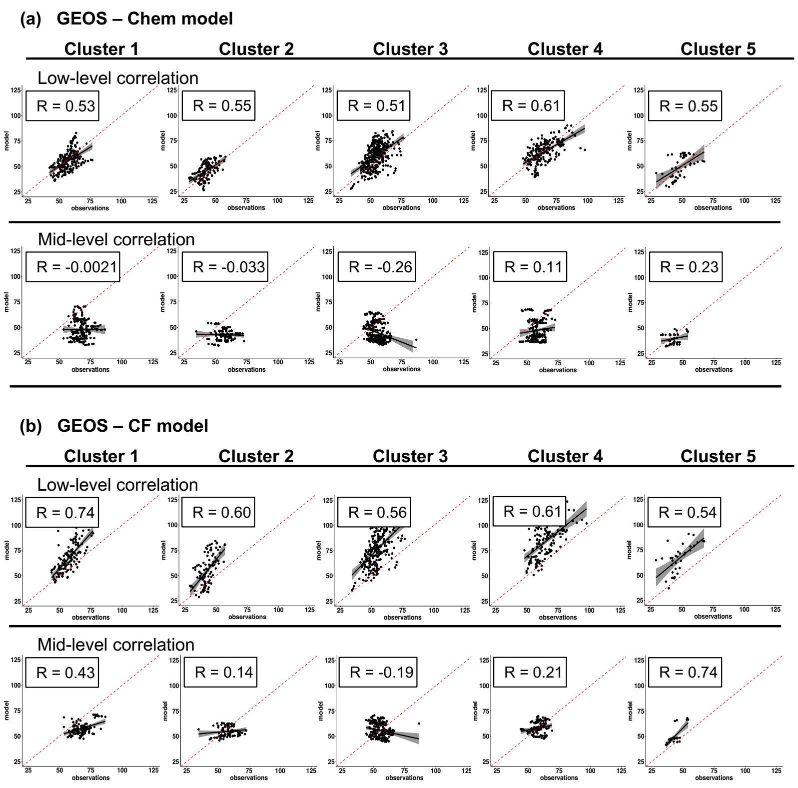
Figure 7 – Please make the limits on the x and y axes the same and add a 1-1 line.
Response: Done.

As mentioned previously, Figure 6 and Figure 7 were accidentally switched in the submitted manuscript, but we corrected this.

New Figure 6 below:



Also updated Figure S4 with same additions:



With the current changes to the manuscript per the reviewer's suggestion to elaborate on cluster specific model insight, we have shifted focused from overall evaluation. Therefore, the previous Figure 6 (above) was moved to the Supplementary Material as Figure S7 and the original Figure S4 has been moved to the manuscript as Figure 7. These changes were made to shift more focus on the different cluster specific model evaluation.

Line 487 – Models are not intended to simulate 'intricate details', but rather the patterns that lead to high/low ozone at the surface. Could you rephrase to discuss how lidar data can contribute to that effort? What can the lidar data provide that surface ozone and sonde data cannot and give specific examples of why this matters.

Response: The manuscript has been updated in Section 3.3.3 to further elaborate on the value of lidar data and its contribution to model simulation. The lidar data provides full temporal but possibly most importantly, vertical observations of O_3 data. This data gives us a fuller story of how O_3 behaves and develops throughout the day and throughout the altitude range. Since we are evaluating full multi-dimensional model curtains, we want to interpretate the vertical profile therefore not only focusing on the surface level performance. Another example that is mentioned in the manuscript explains how the clustering method proves to be more useful in finding cases where concentrated residual layer in the mid-level could have possible entrainment to the low-level/surface. This kind of feature would only be discernable through the use of lidar measurements as O_3 is not only developing from the mid-level to the low-level, but it is developing specifically over a period of time (please refer to Lines 345-346). Although this type of evaluation would need more data to support, the lidar data provides a full characterization of temporal and vertical distribution of O_3 that cannot be provided by other measurements. Another specific example of the importance of using lidar data to evaluate the full temporal and vertical can be found in assessing the GEOS-CF performance in the LLO and LMO cluster. With the multi-dimensional curtain profile, we can indicate that GEOS-CF simulates early morning O_3 very well throughout the low-level. This is different than all the other clusters in which the model overestimates morning O_3 in the low-level. This point is discussed in more detail in the updated Section 3.3.2 and 3.3.3 in the manuscript.

Line 498 – What "additional model performance insight" have you given us? Be more specific.
Response: We fully agree with the reviewer that the discussion needs to be more specific. We have added a more in-depth evaluation of the cluster-to-cluster differences and the value that the clustering approach and lidar measurements bring in Section 3.3.2. and conclusions to Section 3.3.3. In these updated sections we have elaborated on specific model insight that the cluster approach has revealed that is not apparent in the overall model evaluation.

Figure 8 – Why not show a difference plot similar to Fig. 6?
Response: Although this would indeed be helpful in evaluating the wind speed differences, because of the intricacy of the wind arrows on the plots, it is not as feasible to do a difference plot of Figure 8. We would reason to keep the individual curtain wind profiles so that the wind direction differences are easily gaged.

Line 403 – Do the models simulate higher ozone due to insufficient vertical resolution and/or excess vertical mixing? Is there anything to be learned in the only large model underestimate at the surface (GEOS-Chem, HLO)?
Response: GEOS-Chem actually does a fair job estimating the high O_3 in the HLO cluster with only a -0.04 normalized bias. This shows us that GEOS-Chem is able to simulate the extreme cases of high low-level O_3. The model performance conclusions were updated (Section 3.3.2 and 3.3.3).

Line 621 – As these models were run with emissions not provided specifically for the years 2017 and 2018, it might be more informative to look at normalized bias patterns as opposed to absolute biases. As this study is attempting to use the lidar to uncover areas of poor model performance with a focus on coastal meteorology, this approach would remove the impact of emissions not suited to the simulation year.
Response: We agree with the reviewer's suggestion and have updated the analysis to evaluate normalized bias patterns as opposed to absolute biases. Table S1 was updated with the new calculated values and the manuscript was updated with the changes. See the new final Table S1 below:

Table S1. Mean normalized bias & Correlation coefficient (R)					
a) GEOS-Chem Low-level	Cluster 1 - HMO	Cluster 2 - LLO	Cluster 3 - MCO	Cluster 4 - HLO	Cluster 5 - LMO
Bias	- 0.10	0.07	0.13	- 0.04	- 0.09
R	0.53	0.55	0.51	0.61	0.55
b) GEOS-Chem Mid-level					
Bias	- 0.44	- 0.44	- 0.27	- 0.30	- 0.18
R	- 0.002	- 0.033	- 0.26	0.11	0.23
c) GEOS-CF Low-level					
Bias	0.30	0.50	0.67	0.41	0.45
R	0.74	0.60	0.56	0.61	0.54
d) GEOS-CF Mid-level					
Bias	- 0.22	- 0.07	0.05	0.02	0.28
R	0.43	0.14	- 0.19	0.21	0.74

Line 631 – Throughout the paper, 'slightly' better results are not worth describing. Please focus on the most important, high-level results. For example, the finding that the models perform most poorly against the most common cluster is useful. Why do the models do better in cases other than the MCO? Is it because the sea-breeze is the most common pattern and this is most difficult for the models to capture? If so, this is a useful finding and should be more clearly stated.
Response: We agree with the reviewer's comment and have removed cases of 'slightly' better results. We find that with the MCO cluster, the full profile curtain mean reveals a high estimation of early morning O_3. Higher estimated early O_3 can lead to higher afternoon estimations. Additionally, the MCO case in Section 3.4, does consider the possible sea breeze affect leading to higher afternoon estimations of O_3. The wind profile curtain reveals that winds are underestimated in this case which again, also leads to overestimations. These conclusions are divulged in Lines 459 – 472 and in Lines 634 – 637.

Line 659 – You state, "Using the cluster assignments, we are able evaluate how the cluster specific differences reveal additional model performance insight that could be conceivably overlooked when evaluating overall performance." Be specific about the insights you have revealed. The current manuscript is not clear about what the major findings are from the manuscript, nor what the most relevant conclusions are for air quality models.
Response: We have augmented the results and discussion in Section 3 revealing more cluster specific differences as well as supporting the value of the cluster and lidar approach. We also removed any small differences which skewed the scope of the manuscript. The focus is now channeled on the value of the method and what it reveals for air quality models that can be overlooked when evaluating overall performance. Please refer to the updated Section 3.3.2 and Section 3.3.3 for the subsequent changes.

Data availability – The authors need to provide the data links for the observational data used in this study. The authors could also consider providing their clusters as a data product for model evaluation.

Response: The GEOS-Chem model simulation from this study was made publicly available upon submission of the manuscript at https://doi.org/10.7910/DVN/V99LHT. The lidar data is publicly available at https://www-air.larc.nasa.gov/missions.htm (Line 100 - 101). The cluster data can be available upon request.

Reviewer #2:

This manuscript presents the analysis of 91 Lidar measurements of ozone across three different field campaigns along the eastern US coast during the summers of 2017 and 2018 via a clustering analysis and model simulations. The goal of this manuscript was to investigate the characteristics of generalized coastal ozone behavior and to assess the ability of model simulations to reproduce ozone in complex coastal areas. The authors use a K-means clustering algorithm driven by 8 features to cluster their ozone measurements into 5 behavior cases, which they analyzed for different meteorological events that help to describe the ozone behavior in each case. To evaluate model ability to reproduce coastal ozone behavior, two chemical transport models (GEOS-Chem and GEOS-CF) were used to simulate these same events. Both models struggled to capture high ozone concentrations, especially in the mid-level altitudes, and GEOS-CF tended to overestimate low-altitude ozone. Much of this model inability to capture these ozone events was attributed by the authors to an inability to successfully capture changing wind speeds and directions.

This manuscript is a unique analysis and within the scope of ACP. I think it could be a good addition to the literature with some revisions, which I have detailed below.

Major comments:

- The clustering analysis methods needs to be laid out in more depth. Please give a brief description of what a K-means clustering algorithm is, along with most things described in the methods section – Hopkins statistic, silhouette method, etc. How are the best number of clusters chosen? Is this based on variance or something similar? There must be some mathematical model behind the decisions you have made, and this would be helpful to include in the supplemental, along with statistical information that led you to your choice of the number of clusters.

  Response: Following the reviewer's suggestion, we have further elaborated on the clustering algorithm in the Supplementary Material Text S2 - Description of clustering algorithm and cluster efficacy tests. Figure S2, S3, and S4 were added to illustrate the clustering method.

- For the underestimate of ozone in the free troposphere by GEOS-Chem, please include further discussion of model updates that may contribute to this beyond just the lack of the UCX mechanism. Here are papers I suggest reading for more information on the low bias in recent versions of the GEOS-Chem model: halogen chemistry (Wang et al., 2021, doi: https://doi.org/10.5194/acp-21-13973-2021); NOy reactive uptake in clouds (Holmes et al., 2019, doi: https://doi.org/10.1029/2019GL081990); lightning-produced oxidants (Mao et al., 2021, doi: https://doi.org/10.1029/2021GL095740).

Response: This is a great suggestion and we have added these references to the analysis in Section 3.3.3 in Lines 572 - 588.

- The difference in correlations between GEOS-CF and GEOS-Chem (0.69 vs. 0.66) is not large enough to be of any statistical note (both round to 0.7). I suggest removing any discussion of this small difference in correlations. Statistically, the models perform the same.

  Response: We agree with the reviewer's suggestion and have adjusted the manuscript to remove such discussions. Furthermore, Figure 6 has been moved to the Supplementary Materials as Figure S7 and the individual cluster correlations figure (previously Figure S4) has been moved to the main manuscript as Figure 7 to focus on more cluster-to-cluster differences. We thank the reviewer for their constructive comment as it improved the manuscript significantly.

Minor comments:

Line 57: "set out to address this issue" appears twice in the sentence. Please delete one.
Response: Thank you, this was a typo. We have corrected this.

Line 66-69: Ozonesondes are also able to resolve vertical levels. How does the vertical resolution of the lidar measurements compare to ozonesondes? What advantages do lidars have over sondes?
Response: We provided additional examples of the advantages of using the ozone lidar measurements and their value in understanding the full story behavior of ozone development throughout the manuscript. Please refer to Lines 520 – 537, Lines 568 – 571, and Lines 673 – 682 and in general the newly updated Section 3.3.3.

Line 264: "significantly" Please provide a p-value or level of significance.
Response: We are sorry for this confusion as we do not imply a statistical significance. We have removed 'significantly' to avoid further confusion.

Line 406: "modeled versus lidar observation spatial O3 differences" This is confusingly worded. The "differences" implies that you are performing a mathematical operation (model – observed), but what you are doing is plotting model vs observations in Figure 7. Please reword to better express that.
Response: Yes, we are providing the model minus the observed differences to visualize the performances of the models more clearly. I believe the confusion stems from the fact that Figure 6 and Figure 7 were accidentally switched in the submitted manuscript, but we have corrected this. We are sorry for the confusion.

See the correct Figure 7 below:

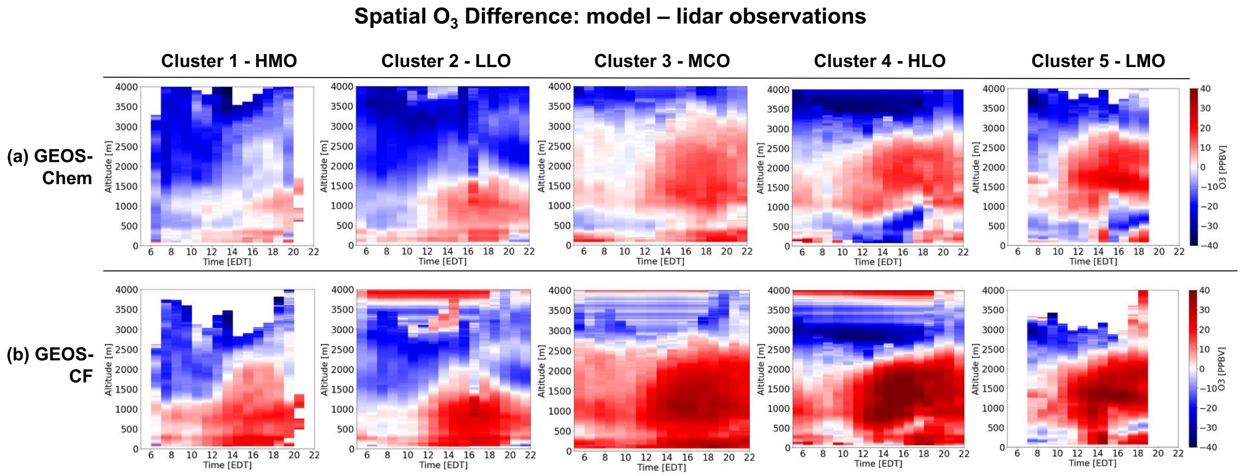


Figure 7. Spatial O_3 difference (model – lidar observations) for each cluster (1 – 5). GEOS-Chem differences (a) and GEOS-CF difference (b).

With the current changes to the manuscript this Figure 7 above is now permanently Figure 6. These changes were made to shift more focus on the different cluster specific model evaluation.

Line 589: Is the underestimate in wind speed and failure to reproduce wind shifts by GEOS-Chem explained by the use of offline meteorology? Some variables in MERRA-2 are averaged every 3 hours, and I assume that sea/bay breezes occur more rapidly than that.
Response: The reviewer makes a very good point. The meteorological variables are averaged every 3 hours which would influence the model's ability to simulate such fine scale temporal changes. Although GEOS-CF does run with online meteorology and does have a slight underestimation of winds as well. We have included this in the analysis.

Line 604-606: It is important to note that GEOS-Chem runs with offline meteorology, averaged every 3 hours. Since sea/bay breezes often happen at a finer temporal resolution, the GEOS-Chem model is at a disadvantage in modelling such fine processes.

Line 652 and 145: "Automatized" should be automated.
Response: Done.

Figures:
Figure 5. Can the observed winds be added to this plot, perhaps as a second row of panels?
Response: Done.

See the updated Figure 5 below:

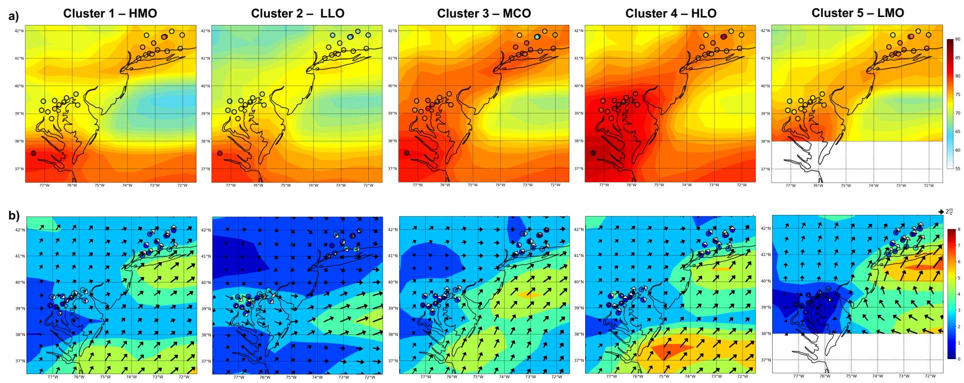


Figure 5. Cluster averaged meteorological surface AQS station observations and GEOS-Chem model results. a) Surface temperature observations represented as the circular markers and simulated surface temperatures represented as the spatial contour (top-panel). b) Surface wind speed and direction observations represented as the circular markers and white arrows and simulated wind speed and direction represented as spatial contour and black arrows (bottom-panel).

Figure S1. Remove Table 2 title from the top of the table.
Response: Done. The figure has been fixed.

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These references have been added to the manuscript. We thank the reviewer for their additions to the manuscript.