Response to Reviewers: “Quantifying biases in TROPESS AIRS, CrIS, and joint AIRS+OMI tropospheric ozone products using ozonesondes”

Reviewer 1:

The study by Pennington et al. exploits ozonesondes to quantify the bias and drift in several satellite records of tropospheric ozone. Overall, this is a nice study providing valuable constraints on TROPRESS products but especially on the methods to QC the ozonesonde data before and after the satellite operators have been applied to the sondes (i.e. allowing for like-for-like comparison between the two). Therefore, this manuscript is suitable for publication in ACP subject to some minor comments.

Thank you for your thoughtful review and helpful suggestions. Your comments have been addressed in the text and described below.

Minor Comments:

Section 2: CrIS, AIRS and OMI have already been defined in Section 1, so do not need to be redefined in Section 2.

This has been updated.

Line 121: Space needed between “15” and “km”.

This has been updated.

Line 162: Should “altitude” be “altitudes”?

This has been updated.

Line 182: Should “compared to climatology” be “compared to a climatology”?

This has been updated.

Line 247: “AIRS’ and CrIS’ error”…should this be error or bias? On line 247 you have used “bias” and “error”. However, they are subtly different things. Please be consistent.

This sentence has been updated to consistently use bias instead of error. We also updated this terminology in other parts of the paper.

Figure S5: The multiple lines for each color (red, black or blue) represent lat bins at 10 degree intervals. However, it is not possible to know which profile is for which lat bin. Or is the main point that they are typically close together? If the latter, please make that clear in the Figure caption or discussion.

This figure has been updated to specify the latitude bins that each profile corresponds to.

Line 260: The authors cite Miles et al., 2015 for the RAL GOME-2 data. A more up to date study in TOAR-2 is that from Pope et al., (2023 - https://acp.copernicus.org/articles/23/14933/2023/acp-23-14933-2023.html) using multiple RAL Space products. Thus, could be useful to cite that ref on line 260 as well.

We originally did not include the satellite-sonde comparisons in Pope et al., 2023 because that paper focuses on the lower tropospheric ozone column rather than the tropospheric ozone column. We have updated that paragraph to include the updated reference: “The median bias of the GOME-2 RAL product compared to ozonesondes in the lower troposphere is approximately -1 DU (-6%) globally, -0.5 DU (-3%) in the NH, and ~0 DU in the SH (Pope et al., 2023). Pope et al. (2023) also quantified the bias of the RAL GOME-1, OMI, and SCIAMACHY lower tropospheric ozone columns compared to ozonesondes. The median bias of RAL GOME-1 is -5 DU (-26%) globally, -5

DU (-26%) in the NH, and -1 DU (-7%) in the SH; the median bias of RAL OMI is -4 DU (-19%) globally, -5.5 DU (-24%) in the NH, and -3.5 DU (-19%) in the SH; and the median bias of RAL SCIAMACHY is 2 DU (12%) globally, 2 DU (11%) in the NH, and 3.5 DU (28%) in the SH."

Line 282: The authors say "A previous study" but it is unclear what the study is. Can you provide the reference in the text?

A citation to Boynard et al., 2018 was added.

Line 318: "Joint AIRS+OMI does not include high ozone values in the Northern high latitudes due to the low joint AIRS+OMI data volume near the poles". Can the authors please expand on this statement as unclear to follow. Why would it not include high ozone values because of low sampling? Would you not expect to have normal levels (be this low or high values relative to other latitude bands) but just a noisier signal as the data volumes are lower?

This sentence has been rephrased to: "The joint AIRS+OMI product has low data volume near the poles and does not properly capture the long tail of the ozone distribution in Northern high latitudes".

Line 320: I know the authors cite Manney et al., 2017 for "multiple tropopauses", however, it might be useful to add a sentence explaining who you get multiple tropopauses.

A sentence was added to describe how multiple tropopauses form: "Multiple tropopauses often form when upper tropospheric jets impinge on the high-altitude tropopause in the tropics, causing high-altitude tropospheric air to "bend" poleward into regions with lower-altitude tropopauses (Manney et al., 2014)".

Table 2-4: It is clear that N is the sample size. However, I cannot see this defined in the Table caption. Thus, for clarity, please do so. Also, e.g. JJA is defined as June/July/August in lots (in not all) instances. You probably only need to define the season(s) once and then use the abbreviations.

We added a description of N to the caption and removed the definitions for seasons since they are defined in Figure 7.

Reviewer 2:

This paper evaluates the TRopospheric Ozone and its Precursors from Earth System Sounding (TROPESS) CrIS, AIRS, and AIRS+OMI ozone products. It quantifies the biases and bias trends in the products compared to quality controlled ozonesonde data to assess the suitability of the products for trend calculations. Multiple methods for quality controlling the ozonesonde data are also considered. The analysis is rigorous and thorough and provides important validation of the TROPESS products. I list general and specific comments below.

Thank you for your thoughtful review and helpful suggestions. Your comments have been addressed in the text and described below.

General Comments

1. While the main focus of the paper is on quantifying biases and trends in bias in the TROPESS products, it would be helpful to provide more discussion of the ozone trends themselves seen in the TROPESS products in order to provide more context for the discussion of biases.

   Our future work will investigate trends in the TROPESS products and consider factors such as satellite vertical sensitivity and horizontal sampling. Additionally, the time period of analysis must be considered because there was a global decrease in tropospheric ozone caused by the COVID-19 pandemic. Because of the complexity of our ongoing trend analysis, we address your comment by adding the following sentences to Section 2.1: "The trends in the TROPESS ozone products are not monotonic due largely to the decrease in ozone during the COVID-19 pandemic (Miyazaki et al., 2021). Therefore, they require careful consideration when being compared to the trends in bias shown in the current study. Such analysis will be the topic of a follow-on manuscript."

2. Since MLS is used to quality control the sonde data, more discussion of how much uncertainty is present in MLS would be helpful to justify this choice.

   In Section 2.2.2 where the MLS data is introduced, we added the sentences: "The accuracy of the MLS-retrieved ozone in the upper troposphere is within 5% compared to ozonesonde data, except in the tropics where the 2σ uncertainty can reach 10% (Livesey et al., 2022)".

Specific Comments

Line 92: Please explain why you focus specifically on SNPP-CrIS

This sentence was updated: "However, for this study we focus only on SNPP-CrIS data so that we use one consistent record (with, e.g., consistent calibration, spatial sampling, and temporal sampling) for our trend analysis".

Line 131: Is the Fu et al joint retrieval the same as what is implemented in MUSES?

Yes, this sentence was updated to clarify that the Fu retrieval and the MUSES retrieval are the same: "This multispectral retrieval, implemented in the MUSES algorithm, uses information in the AIRS TIR bands and the OMI UV bands to produce vertical ozone profiles".

Line 169: sonde operator or satellite operator?

This has been corrected to satellite operator.

Line 217: Please clarify if you are actually using the moving block bootstrapping in this study.

The sentence has been updated to say: "The TOAR-II guidance also provides a method for moving block bootstrapping that we use to calculate the uncertainty of trends and assign a p-value to communicate the likelihood that a trend exists".

Line 239: Does "CrIS errors can be comparable…" mean some individual points in Fig. 5a are comparable, or something else?

This sentence has been updated to provide more clarity: "Joint AIRS+OMI tends to have the largest median bias, but the CrIS median bias can be of a comparable magnitude to joint AIRS+OMI (e.g., Fig. 5b 60-90°N)".

Fig. S5: It's a bit hard to interpret this figure where some of the red or blue lines cross the black lines. Perhaps light to dark shading or different linestyles could be used to indicate which lines correspond to different latitude bands?

This figure has been updated to specify the latitude bins that each profile corresponds to.

Reviewer #3 (Owen Cooper, TOAR Scientific Coordinator)

General comments:

This paper provides a quantification of biases for three tropospheric ozone satellite products. The topic is appropriate for the TOAR-II Community Special Issue and the results are consistent with the results published so far in the Community Special Issue. However, there are a few items that should be addressed, as described below.

Thank you, Owen, for your thoughtful review and helpful and insightful suggestions. Your comments have been addressed in the text and described below.

Please provide additional information regarding the selection of the ozonesonde stations used to evaluate the satellite products. The map of ozonesonde stations in the TOAR-Observations paper (Tarasick and Galbally et al., 2019) shows several current stations across East and Southeast Asia, but they are not shown in your Figure 2, which has no stations in Asia. These regions have been using ECC sondes since the late 1990s or early 2000s, and the Japanese stations go back several decades. In particular, the NASA SHADOZ program launches ozonesondes from Kuala Lumpur and Hanoi, and these locations show very strong ozone enhancements in the lower troposphere, with Hanoi having ozone levels similar to those above China (Gaudel et al., 2024). Another reason to focus on southeast Asia is because this is the only region on Earth where all of the satellite products from TOAR-I showed a positive ozone trend (see Figure 25 of Gaudel et al., 2018).

In this paper, we only analyze harmonized ozonesonde data that was created as part of the TOAR-II project, as described in Van Malderen et al. (2025). Data from 34 sonde sites have been harmonized to "serve three major purposes: (i) removal of all known inhomogeneities or biases due to changes in equipment, operating procedures or processing; (ii) the consistency of records across the ozonesonde network by providing and applying standard guidelines for data (re)processing steps (Smit et al., 2012; appendices C and D in Smit et al., 2021); (iii) providing an uncertainty estimate for each ozone partial pressure measurement in the profile." (Van Malderen et al., 2025). Unfortunately, at the time of submission, some of the remaining sonde sites had not been harmonized. Rather than include all sites that have variable equipment, operating procedures, and processing methods, we have chosen to focus on the harmonized data that have accounted and corrected for these differences. The following sentences have been added to Section 4 to highlight this point: "In this study, we used harmonized ozonesonde data provided by the HEGIFTOM group as part of the TOAR-II project (Van Malderen et al., 2025), which did not include data at all sonde sites at the time of production. For example, some data in East Asia had not yet been harmonized and this could limit our ability to evaluate satellite ozone performance over this region.".

Another important station is the JPL lidar at Table Mountain, north of the LA Basin. Since 2018 this site has been measuring tropospheric and stratospheric ozone profiles 5 times per week. As shown in the recent TOAR-II paper by Chang et al. (2024) high sampling frequency is required for accurate quantification of monthly means and long-term trends. While Table Mountain has only been measuring 5 times per week since 2018, it has been measuring 2-3 times per week since 2000, and therefore has a higher sampling frequency than most sites. Figure 1 (below) shows the long-term trend at Table Mountain (2000-2023) with a positive trend of 0.98 ± 0.93 ppbv per decade (p=0.03). I recommend that these stations be included in your analysis.

In this study we chose to focus on comparisons with sondes rather than the Table Mountain (TMTOL) ozone data because of the technical difficulty of comparing the satellite and lidar data. TMTOL did not measure ozone at pressures greater than 750 hPa until 2018, and therefore comparing the long-term trends in tropospheric columns and lower tropospheric columns is not possible. A comparison of upper tropospheric values is possible, but the comparison is technically challenging because applying the satellite operator requires a full ozone profile, and thus either a climatology or the a priori profile must be used for the lower troposphere. Any discontinuity between the lidar and the lower tropospheric profile would result in errors once the satellite operator is applied.

Additional discussion is required to fully describe the sampling frequency shown in Figure 2b. All of the ozonesonde stations listed here have a sampling rate of 4 profiles per month (or less) with the exception of Uccle, Hohenpeissenberg and Payerne, which launch 3 times per week. Despite the similar sampling rates, the number of data points per month, as reported in Figure 2b, varies greatly. Some of the high latitude sites have 10 or more data points per months, whereas I would expect a maximum of only 4 (because there are just 4 ozone profiles per month). I also don't understand how DeBilt (4 profiles per month) has 16 data points per month (CrIS), while Uccle (just down the road) launches 12 times per month and has fewer data points.

The higher-than-expected sampling frequency is caused by the coincidence criteria which allows a single sonde launch to match to multiple satellite retrievals. The table below provides an example for the Alert, Canada site in January 2019, where 9 separate sonde launches were performed. These 9 profiles correspond to 52 CrIS satellite retrievals that fall within 300 km and 9 hr of the sonde launch location and time (see Section 2.2.1). We have chosen to keep all matches that meet the coincidence criteria and pass both satellite and sonde quality control. This is stated in Section 2.2.1: "These criteria may result in multiple satellite profiles being matched with a single sonde profile".

Sonde date, time	**Sonde lat, lon**	**CrIS date, time**	**CrIS lat, lon**	**Distance between CrIS and sonde (km)**	**Time difference between CrIS and sonde (hr)**
2016-01-06, 23:17:00	79.98, -85.94	2016-01-06, 15:43:53	80.62, -71.6	172.9	7.6
		2016-01-06, 15:44:01	80.69, -77.96	225.5	7.5
		2016-01-06, 17:23:39	82.21, -80.37	205.9	5.9
		2016-01-06, 17:23:55	79.76, -75.64	112.5	5.9
		2016-01-06, 19:06:04	78.22, -92.5	262.2	4.2
2016-01-14, 23:15:00	79.98, -85.94	2016-01-14, 14:52:49	81.4, -82.01	155.3	8.4
		2016-01-14, 14:53:30	78.38, -78.78	184.2	8.4
		2016-01-14, 16:33:38	79.79, -88.45	148.5	6.7
		2016-01-14, 16:33:53	80.55, -74.72	221.0	6.7
		2016-01-14, 16:34:03	78.99, -93.18	172.1	6.7
		2016-01-14, 16:34:11	77.47, -82.8	239.9	6.7
		2016-01-14, 18:14:19	78.94, -81.18	249.3	5.0

2016-01-16, 23:15:00	79.98, -85.93	2016-01-16, 14:15:12	79.84, -91.69	212.0	9.0
		2016-01-16, 14:15:21	79.82, -85.94	96.8	9.0
		2016-01-16, 14:15:45	80.61, -85.32	155.3	9.0
		2016-01-16, 15:55:54	79.02, -76.4	34.1	7.3
		2016-01-16, 17:36:52	78.2, -75.53	212.3	5.6
2016-01-18, 23:15:00	79.98, -85.94	2016-01-18, 15:18:01	79.82, -94.73	118.9	7.9
		2016-01-18, 15:18:34	80.7, -97.21	266.7	7.9
		2016-01-18, 16:58:35	78.19, -83.6	121.7	6.3
		2016-01-18, 16:59:07	79.01, -84.41	161.3	6.3
		2016-01-18, 18:40:11	82.21, -81.24	200.1	4.6
		2016-01-19, 06:36:20	79.91, -77.97	111.8	7.4
2016-01-20, 23:16:00	79.98, -85.93	2016-01-20, 14:40:17	81.43, -90.8	134.9	8.6
		2016-01-20, 14:40:50	79.0, -90.87	246.5	8.6
		2016-01-20, 16:20:43	79.03, -95.49	231.7	6.9
		2016-01-20, 18:01:16	81.47, -88.38	250.2	5.2
		2016-01-20, 18:01:32	82.12, -86.8	209.8	5.2
		2016-01-20, 19:43:56	78.22, -93.22	251.9	3.5
2016-01-22, 04:15:00	79.98, -85.93	2016-01-22, 05:38:12	78.18, -82.78	61.2	1.4
		2016-01-22, 05:38:44	80.57, -82.15	212.5	1.4
		2016-01-22, 09:00:18	81.31, -88.38	175.2	4.8
		2016-01-22, 09:00:26	79.71, -85.15	30.1	4.8
		2016-01-22, 10:41:30	81.41, -78.15	211.5	6.4
		2016-01-22, 10:41:37	78.92, -85.99	275.6	6.4
		2016-01-22, 12:20:57	82.37, -85.24	287.6	8.1
2016-01-23, 11:15:00	79.98, -85.93	2016-01-23, 08:42:11	78.97, -83.69	180.0	2.5
		2016-01-23, 12:04:01	81.4, -84.32	94.5	0.8
		2016-01-23, 12:04:25	80.72, -95.68	263.8	0.8
		2016-01-23, 13:43:36	79.07, -83.61	184.1	2.5
		2016-01-23, 13:44:01	80.55, -79.64	164.8	2.5
		2016-01-23, 15:23:53	82.13, -89.19	218.6	4.1
		2016-01-23, 15:24:02	79.94, -74.01	232.4	4.2
		2016-01-23, 15:24:10	78.2, -78.68	93.1	4.2
		2016-01-23, 15:24:33	78.97, -77.24	69.7	4.2
		2016-01-23, 18:46:11	82.24, -86.01	189.1	7.5
2016-01-26, 04:44:00	79.98, -85.93	2016-01-26, 07:45:15	79.85, -90.7	224.7	3.0
		2016-01-26, 09:25:14	79.09, -98.01	80.8	4.7
		2016-01-26, 11:06:35	78.97, -78.79	298.0	6.4
		2016-01-26, 12:46:25	81.41, -83.64	214.7	8.0
2016-01-27, 23:16:00	79.98, -85.93	2016-01-27, 15:49:38	78.24, -81.2	77.2	7.4

Figure 5 shows results for several latitude bands. Results in the 60S-30S latitude band seem to be based entirely on a single ozonesonde record, from Lauder, New Zealand. This is a very sparse time series with a sampling rate of only about 2 profiles per month. Given the challenges of detecting ozone trends with sparse data records (Chang et al., 2024), how can we have any confidence in the results from this particular latitude band?

The following sentences were added in Sect. 3.2: "The bias trends reported in the 60°S – 30°S band were calculated using data at only one ozonesonde site: Lauder, New Zealand (Fig. 2). While this data may not be representative of the entire latitude band, we choose to include the results because the Lauder site has a relatively high data volume and is an important source of data in the Southern Hemisphere (Fig. 2b). Additionally, the profiles of satellite-sonde bias at the Lauder site (Fig. 4) display similar features as the profiles in other latitude bands, suggesting that the Lauder site provides meaningful data. The ability of one site to represent trends throughout a region is discussed further in Sect. 4". This sentence was also added to Sect. 4: "There is only one sonde site providing harmonized data between 60°S and 30°S (Lauder, New Zealand) and there is no harmonized sonde data available below 60°S".

Specific Comments:

Lines 17-19: Gaudel et al. (2018) is a paper that is now 7 years old and it is out of date regarding global tropospheric ozone trends. IPCC AR6 (see section 2.2.5.3 in Gulev et al., 2021) assessed the results from TOAR as well as papers published after the first phase of TOAR ended, and the consensus conclusion was that the global tropospheric ozone burden had generally increased (see section 2.2.5.3 in Gulev et al., 2021).

The text has been updated to reflect this newer source of data. In the previous version, Gaudel et al. (2018) was cited in both the Introduction and Results sections and we stated that tropospheric ozone trends spanned a range of approximately -2.15 Tg year^{-1} to 2.85 Tg year^{-1} and there was no consensus among satellite products. In the updated manuscript, we instead state that Gulev et al. (2021) found consistently increasing trends. We also note that Gulev and most other studies in Table 1 focused on UV and/or visible and/or near IR retrievals of ozone, whereas AIRS and CrIS retrieve ozone in the thermal IR range.

In the first paragraph of the Introduction, we rephrased our motivation to focus on the magnitude of disagreement between satellites rather than the sign of the TOB trends reported by Gaudel et al. (2018): "Tropospheric ozone trends show large regional variations and can depend strongly on the type of measurement analyzed, coverage, frequency, and vertical sensitivity. The Tropospheric Ozone Assessment Report (TOAR, https://igacproject.org/activities/TOAR) aims to provide the most complete assessment of tropospheric ozone available to the community by compiling a comprehensive database of ozone measurements and analyzing data from multiple sources holistically. The Sixth Assessment Report (AR6) produced by the Intergovernmental Panel on Climate Change (IPCC) reports that the global tropospheric ozone burden (TOB) is increasing, but regional trends detected by three ensembles of satellite data ranged in magnitude from 2% decade^{-1} to 14% decade^{-1} (Gulev et al., 2021). The ensembles in Gulev et al. (2021) combine satellite instruments that retrieve ozone in the ultraviolet (UV), visible, and/or near infrared (NIR) ranges, but does not include instruments that retrieve ozone in the thermal infrared (TIR) range. Some TIR instruments have reported negative tropospheric ozone trends in various regions (e.g., Pope et al., 2024; Dufour et al., 2025). The satellite assessment in Phase 1 of TOAR (TOAR-I) (Gaudel et al.,

2018) speculated that causes of inter-satellite disagreement include differences in each instrument's vertical sensitivity to the atmospheric profile of ozone, spatial sampling across the globe, and measurement period".

In Section 3.2, the magnitude of global trends were compared to the range of satellite trends in Gulev et al. (2018): "Gulev et al. (2021) reported regional TOB trends ranging from 2 to 14% decade^{-1} (1-6 ppbv decade^{-1}). Globally, the trends in bias fall below the low end of that range (2% decade^{-1}) by a factor of 1-10".

The satellite-derived tropospheric ozone column trends from Gulev et al. (2021) have also been added to Table 1.

Table 1 needs to also include the satellite trends reported by two recent TOAR-II publications: Pope et al. (2023) and Froidevaux et al., 2025.

These data and references have been added to Table 1.

Line 137: The description of the ozonesonde method is not correct. The radiosonde measures pressure, temperature and relative humidity, while the actual ECC ozonesonde instrument simply measures the electrical current produced by the reaction of ozone in a potassium iodide solution. See Section 4.3 in Tarasick and Galbally et al., 2019. Also, ozonesondes typically reach altitudes above 30 km, so the lowest pressure that they reach is much lower than 80 hPa (as shown in your Figure S1). If I think back to the days when I launched ozonesondes, I believe they routinely reached pressures below 30 hPa.

The description has been corrected in Section 2.2: "ECC sondes are mounted alongside radiosondes to provide the partial pressure of ozone, total atmospheric pressure, and atmospheric temperature (Tarasick et al., 2019). These quantities can be used to calculate the volume mixing ratio (VMR) of ozone throughout the profile until the balloon pops, typically before reaching 5 hPa".

Supplement, line 45: Here, do you mean to say that the sonde stopped measuring at low pressure (i.e. in the stratosphere) rather than at low altitude (i.e. the boundary layer)?

Some sonde measurements do not extend beyond the troposphere because the balloon popped while still in the troposphere. The methods described here (e.g., minP_70, etc.) describe these cases. The sentence has been modified to be clearer: "Some of our other Step 1 methods instead remove profiles in which the sonde stopped measuring at lower-than-average altitudes in the troposphere (i.e., minP_70, minP_60, minP_50, minP_TP), so they do not provide sufficient information in the stratosphere".

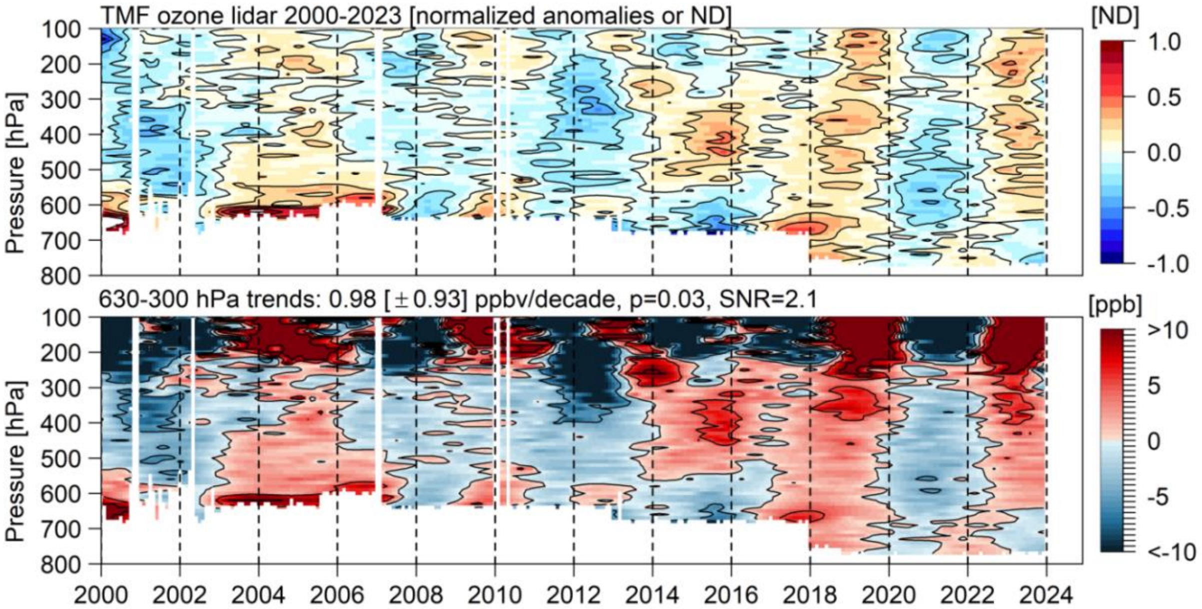

Figure 1. Ozone variability and trends based on the JPL Table Mountain lidar, following the methods show in Figure 3 in Chang et al. (2023). The mid-tropospheric 2000-2023 ozone trend is 0.98 ± 0.93 ppbv per decade (p=0.03).

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