

Reviewer 2 Response:

We thank reviewer 2 for their time and thoughtful response to the manuscript. The responses to each comment are below where the authors' responses are bolded. New additions are in quotation marks and updated line numbers are included.

Changes made in marked Manuscript: **Reviewer 1** **Reviewer 2** **BOTH**

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**Reviewer 2: PURPLE**

Review of "Evaluation of Pandora HCHO and NO<sub>2</sub> with Airborne In Situ Observations"

This manuscript presents a valuable evaluation of Pandora HCHO and NO<sub>2</sub> profile measurements using airborne in situ observations. The study is well designed, the analysis is generally robust, and the results are relevant for the validation of ground-based and satellite air quality products. Overall, the paper makes a meaningful contribution. The conclusions are clearly written and appropriately summarize the key findings, and the discussion of the New York flight conditions is particularly clear and well presented. I especially appreciate that the authors highlight the importance of coordinated aircraft and Pandora observations in future work. I recommend this manuscript for publication after addressing the comments and minor revisions outlined below. Below are specific comments and suggestions intended to improve clarity.

General and Section-Specific Comments

1. The conclusion that differences in NO<sub>2</sub> are primarily driven by spatial heterogeneity, while HCHO profiles show better agreement, is not strongly supported by Figure 3. As stated in the abstract, MAX-DOAS NO<sub>2</sub> is reported to be ~80% lower for the entire profile and particularly sensitive to the Pandora viewing angle due to NO<sub>2</sub> spatial heterogeneity. To better support this conclusion, it would be valuable to demonstrate whether the observed biases decrease when the aircraft data are restricted to sampling along (or close to) the Pandora pointing azimuth. In addition, it would be helpful to clarify whether spatial heterogeneity varies with altitude (e.g., being stronger near the surface and weaker aloft).

**Limiting the comparison of Pandora NO<sub>2</sub> columns to in situ NO<sub>2</sub> only within or close to the PAA proved difficult as the aircraft did not sample near the surface in the top right quadrant (Fig. 2b), only in the bottom right includes in situ observations below 0.5 km. Aloft, where the aircraft was flying in concentric circles around the Pandora, the NO<sub>2</sub> is well mixed and there is no difference in NO<sub>2</sub> agreement based on azimuth angle. The comment regarding spatial heterogeneity primarily reflects strong near-surface enhancements that are not fully captured within the Pandora viewing geometry. Above the**

**boundary layer, NO<sub>2</sub> is more uniformly mixed, and agreement between aircraft and Pandora observations improves.**

**Spatial heterogeneity does vary with altitude, with little variation aloft. Line 198 has been changed to clarify this: “The in situ NO<sub>2</sub> is more variable than HCHO, primarily near the surface”.**

2. Introduction:

The introduction is concise and effective. However, adding a few lines describing the geographical regions studied (e.g., New York, Long Island Sound, Edwards CA) would help orient readers early in the manuscript.

**More details on the geographical regions have been added in the introduction (line 64)**

3. Line39:

Please include SO<sub>2</sub> and water vapor columns among the Pandora products, and clarify that total ozone is retrieved (i.e., no partial ozone product is available).

**These products have been included. (line 39)**

4. Table1:

In the table caption, please clarify that the listed pointing azimuth angles correspond to sky-scan (MAX-DOAS) observations.

**Table captions have been updated (line 109).**

5. Line218:

Please explicitly refer to Figure 3 when discussing these results.

**Figure 3 has been included in this sentence (line 224)**

6. Line221/Section2.2:

Please add a brief explanation of the “no filter” vs. “yes filter” cases to help readers interpret Figure S6.

**Figure S6 caption has been updated to explain the filters better. SI Text 3 explains these differences in greater detail.**

7. Lines 223–224:

Please confirm that the 10 m altitude refers to above ground level (AGL). Also discuss whether the missing column from the surface to 10 m could contribute to the observed differences between Pandora and aircraft columns.

**We have clarified that 10m is AGL (line 239 and 240) with the comment: “For the in situ column integration, the HCHO and NO<sub>2</sub> observed at the lowest height (10m) are assumed to be constant from 10m to the surface”. Table 2 caption has also been updated (line 233).**

#### 8. Tables (general):

Please expand table captions to be more descriptive, making them more self-contained for readers.

**Greater detail has been added to all table captions.**

#### Interpretation and Methodology Clarifications

##### 1. Line 248:

The higher near-surface Pandora columns for both NO<sub>2</sub> and HCHO warrant further discussion. Could this be related to the aircraft spiral sampling a broader horizontal area? Please consider including the range of spiral radii at different altitude.

**Except for the highest altitudes which are not included in Fig. 2, the aircraft spiral is within the maximum horizontal range on the Pandora MAX DOAS. The red line in Fig. 2 shows the actual distance. Since NO<sub>2</sub> is well mixed above the surface enhancement, the horizontal distance from the aircraft and the Pandora is unlikely responsible for the disagreement in NO<sub>2</sub>, particularly near the surface where the aircraft was sampling in tighter circles. This is different from the NYC cases where oftentimes the aircraft was sampling outside of the max horizontal distance.**

**Within the scope of this study, we are unable to present a cause of this vertical bias in either HCHO or NO<sub>2</sub>. However, it is consistently seen in several case studies (EdwardsAFB, NYC3). A more detailed investigation of the Pandora retrieval algorithms is required to determine the source and develop a solution to this bias.**

##### 2. Line 250:

The term “integrated column” for MAX-DOAS needs clarification. Are the authors integrating profile layers themselves, or are they using independently retrieved tropospheric columns from sky-scan/MAX-DOAS? Typically, MAX-DOAS columns are retrieved directly and not calculated by vertically integrating profiles. Please clarify and revise wording if needed.

**In this instance, “integrated column” refers specifically to the vertically integrated in situ measurements derived from the aircraft observations. We have clarified this terminology in the manuscript to avoid confusion with MAX-DOAS tropospheric column products. (line 241).**

3. Line 255:

Could the DS NO<sub>2</sub> measurements be influenced by airport emissions during morning observations due to pointing azimuth angles? It would be useful to examine how the difference between DS and SS NO<sub>2</sub> columns varies with solar azimuth – pointing azimuth.

**Supplemental figure S9 has been added (line 128-134 in supplemental) showing the agreement between DS and SS NO<sub>2</sub> as a function of solar azimuth angle of the DS measurements. In this Pandora the agreement between DS and MAX DOAS NO<sub>2</sub> is not dependent on the azimuth angles.**

The azimuth angle for the MAX DOAS measurements is always 30 degrees (NE) for this Pandora. The DS azimuths range from 60-300 degrees.

4. Lines 260–261:

I doubt that MAX-DOAS has sensitivity up to tropopause altitudes. Please clarify or revise this statement.

**Statement has been revised to “higher altitudes”. (Line 278)**

5. Line 263:

I may be missing, but I do not see a clear comparison of NO<sub>2</sub> MAX-DOAS profiles or columns restricted to aircraft sampling along (or near) the pointing azimuth direction. If this analysis is included under the “no enhancements” category in Table 2, please explicitly mention and cite it.

**We did not include a direct comparison only in the pointing azimuth direction. The field of view of the Pandora is 2.5° (the red line in Fig. 2 shows the actual range). Because of this small width only a few aircraft points would technically fall in the azimuth direction, none of which occurred near the surface in the altitude range of the surface enhancement. Because in situ NO<sub>2</sub> is relatively well mixed above 0.5 km, this azimuth angle comparison was not helpful in this case study. We discussed the importance of NO<sub>2</sub> spatial heterogeneity because future airborne field campaigns should make sure to take the PAA into consideration for this purpose.**

6. Line 283:

Please clarify whether the reported HCHO values are based on aircraft data, and/or cite Figure 4.

**In situ HCHO and figure 4 have been explicitly stated in this sentence (line 299).**

7. Line 326:

Rawat et al. (2025) reported issues with Manhattan observations. Similar behavior appears evident here. I recommend adding a brief statement acknowledging known Pandora DS limitations at this site.

**The following sentence has been added to line 349 to address this: “ManhattanNY-CCNY has been cited as a lower confidence Pandora in previous (Rawat et al., 2025), likely due in part to obstructed viewing from surrounding tall buildings.”**

8. Line 360:

There is some confusion here. Even though the Edwards CA aircraft profile extends from 0.1 to 10 km, MAX-DOAS sensitivity is typically limited to ~2–3 km. Please clarify why the New York spiral (0.1–2 km) is considered less ideal in this context.

**Clarification on line 383-386. Comparisons cannot be made with DS total columns. We choose to only integrate the MAX DOAS partial columns to altitudes that the aircraft sampled, and not use the Tropospheric Column provided.**

9. Line 375:

Please note that the 77% in situ–Pandora difference at New Haven, CT may also be influenced by the limited vertical representativeness of the aircraft profile.

**We only compare altitudes where both the aircraft and Pandoras overlap so it is possible we are missing potential biases near the surface. While we restrict comparisons to overlapping altitude ranges, differences in horizontal sampling extent and spatial representativeness may still contribute to discrepancies between aircraft and Pandora columns. We have added clarification about this on line 395-397 and 399-400.**

10. Line 381:

The Long Island Sound (LIS) region frequently experiences ozone exceedance events and is often downwind of major emission sources. One might therefore expect higher HCHO. Could you justify the lower HCHO values over LIS using aircraft data and, if possible, please provide values?

**Thank you for this remark. We have removed the comment about HCHO in the LIS. Most of the DC-8 profiling was done over the LIS, just west of where the Pandora is pointing. Instead, we discuss again the spatial differences in sampling and that most of the bias in columns are above the Boundary Layer (lines 411-414).**

Figures and Spatial Interpretation

1. Section 3.2.3:

Please explain why only TEMPO HCHO is evaluated in this section. Alternatively, I encourage the authors to conduct a similar TEMPO assessment for NO<sub>2</sub>, comparable to the thorough HCHO evaluation presented. Similarly, why no comparison of TEMPO columns with aircraft observations.

**This study focuses on HCHO because it has received significantly less validation in Pandora observations compared to NO<sub>2</sub>, for which multiple validation studies already exist. In addition, a complementary analysis of TEMPO NO<sub>2</sub> using in situ observations is currently being conducted separately. To maintain a clear and focused scope, we therefore limit this study to HCHO evaluation, where the need for validation is greater.**

**Due to the limited number of vertical profiles conducted by the aircraft, as well as the need for relatively large spatial averaging of TEMPO HCHO, we do not directly compare airborne HCHO to TEMPO HCHO.**

2. Lines 427–445 / Figure 5:

Please clarify whether the TEMPO diurnal profiles are derived from:

- a. all pixels within the New York domain, or
- b. first collocated with Pandora and then averaged.

Revising this section for clarity would greatly improve interpretation.

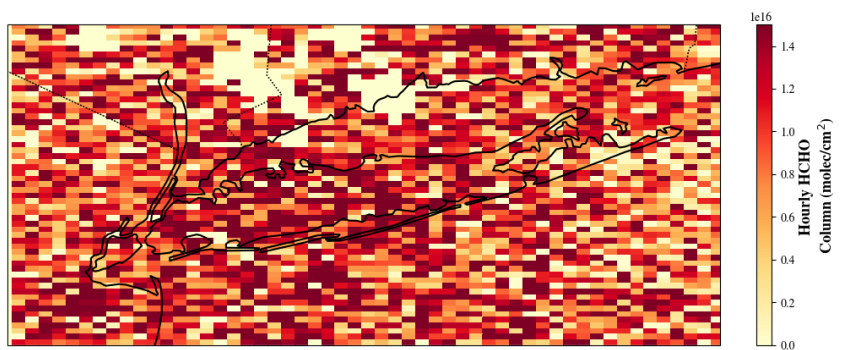
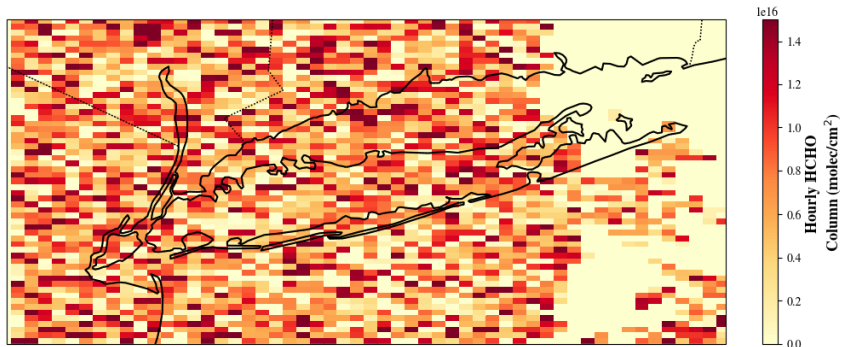
**The following sentence has been added to line 460 “These values correspond to column averages over the entire NYC domain as shown in Fig. 4.”.**

**Fig. 5 figure caption has been updated (line 357).**

3. Figure 8:

Please describe the spatial domain and collocation criteria used. Also discuss how the choice of domain may influence the observed biases.

**Fig. 8 figure caption has been updated. The following lines have been added (lines 506-510) “There is also potential bias associated with the choice of domain used for the TEMPO averaging. Due to the uncertainty and noise in TEMPO HCHO retrievals, a relatively large area is required for spatial averaging. However, portions of this domain extend over the ocean where HCHO columns may be lower than what is observed by the Pandoras. This may cause a low bias in the TEMPO HCHO.”**



**TEMPO column HCHO in NYC at 8 am EDT (top) and 11 am EDT (bottom) on August 8<sup>th</sup>, 2023.**