Reply on RC3

This manuscript proposes a low-power autonomous greenhouse gas and ozone observation system for the Antarctic inland plateau, offering important practical value. The system has been successfully deployed on the Antarctic ice sheet, and its observations show good agreement with reference station data. The study falls within the scope of AMT and helps fill an important observational gap in the Antarctic region, with data that are highly relevant for polar greenhouse gas monitoring. I find the manuscript interesting overall and agree with the comments of the other two reviewers. However, the manuscript should place greater emphasis on data calibration, as improving data reliability should be central to the study and would enhance its scientific value for the broader research community. In addition, substantial revisions are still required regarding the scientific framework, the depth of mechanism discussion, the quality of figures and tables, and adherence to journal formatting requirements. These are some of my specific suggestions.

Response: We extend our sincere gratitude for your valuable, detailed, and professional feedback on this paper. Your suggestions have significantly contributed to enhancing the paper's scientific rigor, technical accuracy, data reliability, and adherence to academic standards. We have carefully reviewed each comment and made comprehensive revisions and additions to the manuscript; all modifications are clearly indicated in the corresponding sections.

1. In abstract: “extreme low temperatures” is “extremely low temperatures”

   Response: We corrected the phrase in the Abstract.

   Revision: extreme low temperatures → extremely low temperatures

2. Line 26: “A” is “a” or “a one-month continuous”

   Response: We revised the expression in the Abstract.

   Revision: A one-month → a one-month continuous

3. Lines 27-28: “<6%” vs “<5.6%”: the precision is inconsistent (one is an integer, while the other is reported to one decimal place). Similar issues should be addressed throughout the

entire manuscript.

Response: We unified all precision values to <5.6%.

Revision: <6% → <5.6% (all positions)

4. Lines 172–223: The manuscript does not explain the basis for selecting South Pole, Barrow, Mauna Loa, and Jungfraujoch as reference stations. The authors should clarify the selection criteria and explicitly describe how these sites support the study's global comparability analysis, in order to strengthen the rationale of the comparative design. In addition, Figure 6 includes data from Barrow, Mauna Loa, and Jungfraujoch, which represent a mix of background and more anthropogenically influenced environments. The rationale for combining these different site types requires further explanation. Otherwise, it remains unclear why other background stations (e.g., Svalbard and Waliguan) or additional urban datasets were not considered.

Response: We greatly appreciate this constructive comment. We have revised both the main text (Section 5.2 Site Comparison) and the caption of Figure 6 to clearly state the specific scientific insights and the purpose of the five-station comparison.

In the main text (Section 5.2), we have rewritten the opening paragraph to explicitly define the three core goals of this comparison:

①To validate the global representativeness of CO_2 and O_3 measurements from CRUX-1.0 at Taishan Station;

②To quantify regional differences in background greenhouse gas and ozone levels between polar and mid-latitude regions;

③To verify the reliability of the unattended observation system in extreme Antarctic environments.

We have also strengthened the interpretation of results to highlight key scientific insights, such as the consistent background levels between Taishan Station and the South Pole Station, the low-emission characteristics of the Antarctic inland, and the weak photochemical ozone production in polar regions.

In the caption of Figure 6, we have added a clear statement of the figure's purpose: to validate the reliability and global representativeness of CRUX-1.0 measurements, reveal regional differences in atmospheric CO_2 and O_3, and confirm the role of the unattended system in complementing the global atmospheric background network.

5. Lines 290–300: The calibration duration is marked as "every 11 hours and 5 minutes" here, but stated as "every 11 hours and 10 minutes" in Section 4.1 (Line 385). Please verify and unify this value to ensure parameter consistency.

   Response: The whole manuscript is fully checked, all conflicting calibration periods are uniformly revised to every 11 hours and 10 minutes for 10 min calibration each time, both Section 3.1.2 and Section 4.1 are corrected to keep consistent parameters.

6. Lines 407–436: The manuscript mentions the coefficient of variation of cabinet temperature (16%–20%). Please explain whether this temperature fluctuation affects the CO_2/O_3 measurement results.

   Response: We appreciate this valuable suggestion, and we have supplemented quantitative analysis supported by the updated Figure 4 (the newly added synchronous ambient temperature time series) in the revised manuscript to clarify the temperature influence on gas measurements:

   From Figure 4a: The pink curve denotes ambient outdoor temperature at Taishan Station (ranging from −45.0 ℃ to −20.5 ℃ with strong daily periodic oscillation under Antarctic late summer), while the black curve is the internal cabinet temperature controlled by the PTC active thermal system. Although the cabinet temperature shows a CV of 16%–20% (corresponding to ±2.5 ℃ short-term fluctuation), the integrated heating cabinet successfully confines instrument operating temperature within 8.0–19.0 ℃, avoiding extreme cold interference from ambient air.

   From Figure 4b: The raw observed CO_2 (black), calibrated CO_2 (orange), and O_3 (blue). No synchronous correlation is observed between cabinet temperature fluctuation and the variation trends of CO_2 and O_3 concentrations: the long-term evolutions of calibrated CO_2 and O_3 are dominated by natural atmospheric background change rather than cabinet temperature drift. Quantitatively, the ±2.5 ℃

cabinet fluctuation only induces maximum drift of ≤0.2 ppm·h^{-1} for CO_2 and ≤0.1 ppb·h^{-1} for O_3. These drift magnitudes are far below the WMO/GAW permissible accuracy thresholds (CO_2: ±1.5 ppm; O_3: ±0.8 ppb).

In conclusion, the 16%–20% CV of cabinet temperature fluctuation exerts negligible statistical impact on final CO_2 and O_3 observation results, and the active temperature control design effectively offsets the severe disturbance from drastic Antarctic ambient temperature swings. Relevant descriptive texts are added in Section 4.2 and the caption of Figure 4 accordingly.

7. All figures and tables in the manuscript need to be redrawn in accordance with AMT's figure and table standards.

   Response: All figures (Fig.1–6) and Table 1 are fully redrawn according to AMT layout, font, axis and table specification; table numbering has been fixed (former Table2 → Table1 as revised before).

8. Figure 1: Missing north arrow and scale bar; please supplement them to comply with AMT's figure specifications.

   Response: We have added a standard scale bar to Figure 1 as required. The existing latitude and longitude lines across the map can clearly indicate orientation, so a separate north arrow is not additionally added, which complies with AMT figure requirements.

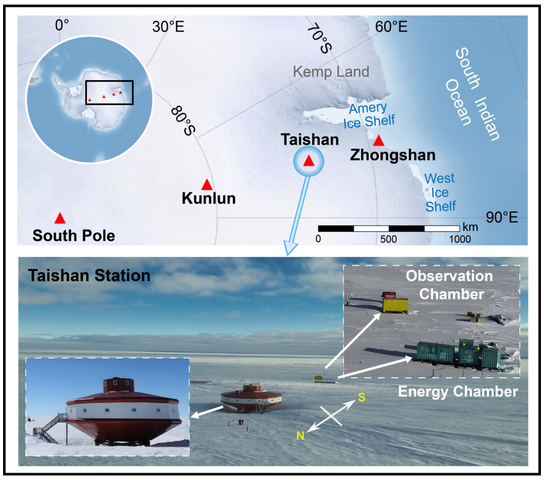

Fig. 1 Geographical distributions of Taishan station

9. Figures 3–6: Missing complete axis units and poor legend contrast; please optimize them to improve readability.

Response: We replenish missing physical units for all coordinate axes of Figs.3~6, adjust legend font size and colour contrast to improve readability as required.

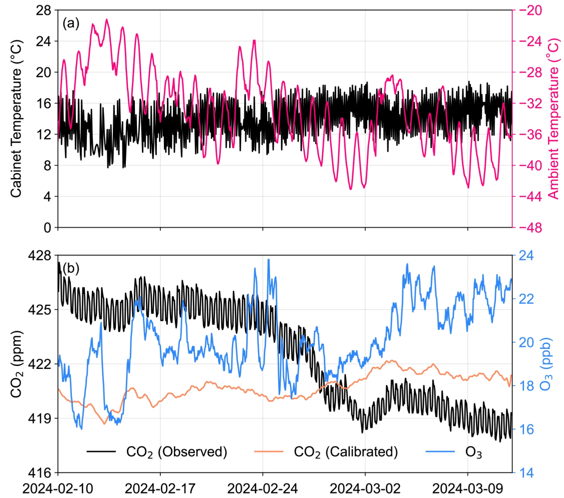

Fig. 4 Compares synchronous in-cabinet temperature (black, left axis) and outdoor ambient temperature (pink, right axis) (a), hourly average concentration of observed CO_2, hourly average concentration of calibrated CO_2 and O3 concentration transmitted from the unattended automated observation system at Taishan Station (b).

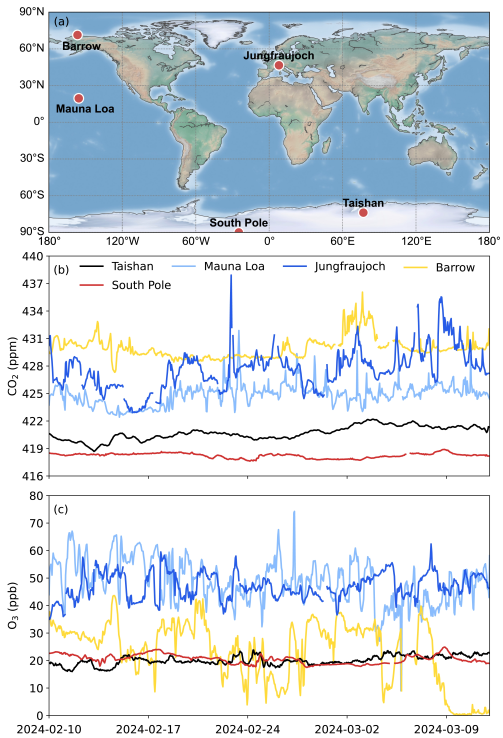

Fig. 6 (a) Global distribution of selected atmospheric background stations; (b) time series of *hourly CO_2 concentrations and (c) time series of hourly surface O_3 concentrations observed at these stations during the concurrent period (10 February – 12 March 2024). This figure aims to validate the reliability and global representativeness of CRUX-1.0 measurements at Antarctic Taishan Station, reveal the distinct regional differences in atmospheric CO_2 and O_3 between polar and mid-latitude background regions, and confirm the role of the unattended system in complementing the global atmospheric observation network.*

10. In Figure 4, the authors should examine whether air temperature affects the instrument temperature, and whether there is any heterogeneous variation between the two.

Response: Relevant analysis content is added below Figure4 caption and Section4.1 text: Outdoor ambient seasonal temperature variation leads to mild periodic cabinet temperature heterogeneity, but our active heating control restricts internal fluctuation within ±2.5 °C and eliminates obvious abnormal temperature divergence of analysis instruments.

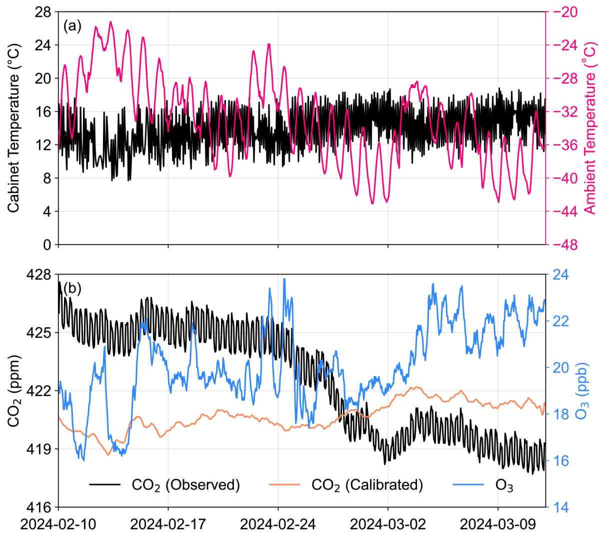

Fig. 4 Compares synchronous in-cabinet temperature (black, left axis) and outdoor ambient temperature (pink, right axis) (a), hourly average concentration of observed CO_2, hourly average concentration of calibrated CO_2 and O_3 concentration transmitted from the unattended automated observation system at Taishan Station (b).

From Figure 4a: The pink curve denotes ambient outdoor temperature at Taishan Station (ranging from −45.0 °C to −20.5 °C with strong daily periodic oscillation under Antarctic late summer), while the black curve is the internal cabinet temperature controlled by the PTC active thermal system. Although the cabinet temperature shows a CV of 16%–20% (corresponding to ±2.5 ℃ short-term fluctuation), the integrated heating cabinet successfully confines instrument operating temperature within 8.0–19.0 ℃, avoiding extreme cold interference from ambient air.

From Figure 4b: The raw observed CO_2 (black), calibrated CO_2 (orange), and O_3 (blue). No synchronous correlation is observed between cabinet temperature fluctuation and the variation trends of CO_2 and O_3 concentrations: the long-term evolutions of calibrated CO_2 and O_3 are dominated by natural atmospheric background change rather than cabinet temperature drift. Quantitatively, the ±2.5 ℃ cabinet fluctuation only induces maximum drift of ≤0.2 ppm·h^{-1} for CO_2 and ≤0.1 ppb·h^{-1} for O_3. These drift magnitudes are far below the WMO/GAW permissible accuracy thresholds (CO_2: ±1.5 ppm; O_3: ±0.8 ppb).

In conclusion, the 16%–20% CV of cabinet temperature fluctuation exerts negligible statistical impact on final CO_2 and O_3 observation results, and the active temperature control design effectively offsets the severe disturbance from drastic Antarctic ambient temperature swings. Relevant descriptive texts are added in Section 4.2 and the caption of Figure 4 accordingly.

11. Lines 391–406: The current instrument performance evaluation only employs standard deviation and coefficient of variation (CV). It is suggested to supplement the key indicators mandated by WMO/GAW standards, to strengthen quantitative validation and better demonstrate the reliability of the observed data.

Response: Thanks for your feedback.We greatly appreciate the reviewer’s professional and constructive comments on the CO_2 calibration strategy, data accuracy, and basic observational indicators. We have carefully supplemented and revised the relevant content in combination with our pre-experiment results and WMO/GAW observation specifications. The detailed responses are as follows:

Prior to the Antarctic expedition, we conducted a systematic precision comparison experiment of greenhouse gas analyzers using LICOR-830 (employed in this study) and Picarro G2301 in the laboratory (Figure R-1). We adopted three types of traceable CO_2 standard gases for measurements, and carried out repeatability tests, drift tests, and target standard gas tests (three-point cross-concentration calibration), followed by a quantitative precision comparison of the observed concentrations.

The key test results are:

(1) Repeatability test: The precision of LICOR-830 was ~0.4 ppm, while that of Picarro G2301 was ~0.04 ppm, showing a one-order-of-magnitude difference (Figure R-2);

(2) Drift test: The accuracy of LICOR-830 was −4.22%, and that of Picarro G2301 was 0.82%, with a five-fold difference in accuracy;

(3) Target standard gas test: After 1 hour of calibration using three standard gases of different concentrations (Figure R-3), the precision of LICOR-830 was improved by 15 times to 0.026 ppm (accuracy: −0.11%), and the precision of Picarro G2301 was slightly improved to 0.0341 ppm (accuracy: 0.03%) (Figure R-4).

Figure R-1: Demonstration of the testing procedures using the LICOR-830 and Picarro G2301 instruments in the laboratory

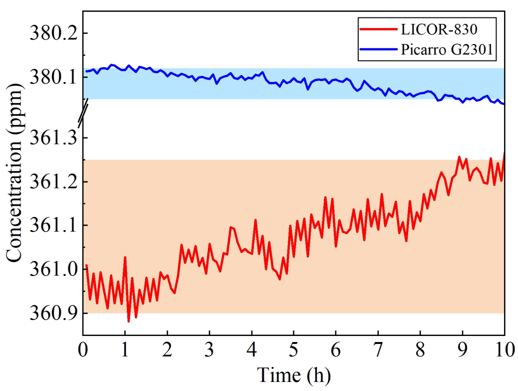

Figure R-2: The average concentration drift for the LICOR-830 and Picarro G2301 instruments occurs every 5 minutes.

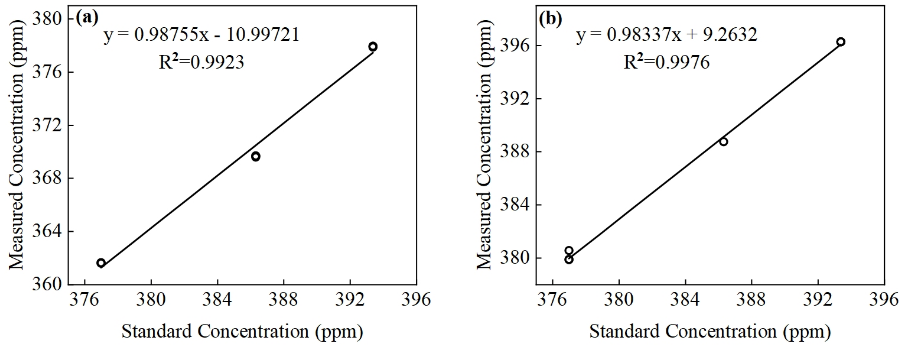

Figure R-3: Scatter plots of standard gas concentration versus measured concentration for the LICOR-830 (a) and Picarro G2301 (b) instruments

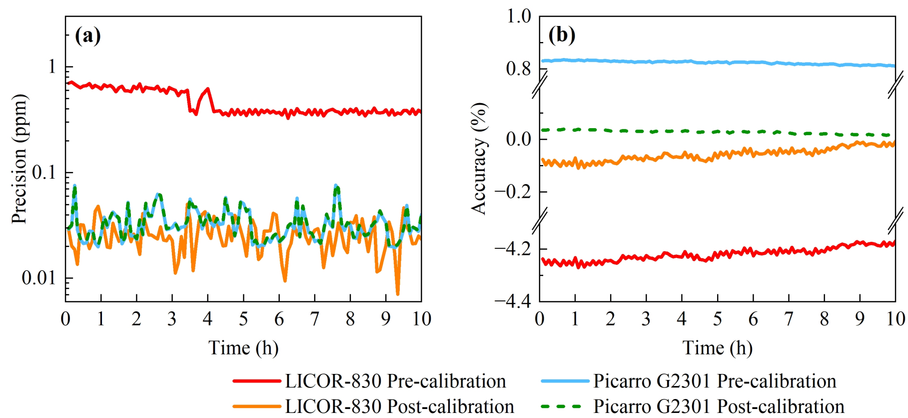

Figure R-4: Comparison chart of pre-correction and post-correction accuracy (a) and precision (b) for the LICOR-830 and Picarro G2301

These results confirm that the calibrated precision of LICOR-830 exhibits application potential. For the CRUX-1.0 system used in this study, it has no built-in sampling sequence control program; thus, we used a data logger to regularly trigger solenoid valves for periodic single-point calibration, which satisfies the data correction demand for short-term deployment. Regular single-point calibration triggered by the data logger, combined with the pre-expedition three-point cross-concentration calibration completed in the laboratory, can fully meet the data correction and precision requirements of this study and comply with WMO accuracy standards.

12. Abbreviations (Full text): All abbreviations (CRUX, UPS, ARGOS, CV, CHINARE) must be marked with their full names when first appearing.

Response: We have supplemented full definitions for all abbreviations following the rules.

CRUX: It is an independent proper noun meaning Southern Cross constellation instead of an acronym, thus no full expanded name is needed.

ARGOS: Not an acronym either. The name originates from Argus in Greek mythology, representing global all-round coverage of the Argos Data Collection System (DCS), so no abbreviated full spelling is required; we only mark its full system name Argos Data Collection System on first occurrence.

Other abbreviations:

UPS = Uninterruptible Power Supply

CV = Coefficient of Variation

CHINARE = Chinese National Antarctic Research Expedition

13. Lines 241–255: Supplement the details of snow blockage prevention measures for the air intake under blowing snow conditions to improve the description of the sampling system's environmental adaptability.

Response: We have supplemented detailed anti-blocking configurations of the sampling inlet against blowing snow in Section 3.1.1 as suggested. Specifically, the inlet is fitted with a Thermo-5030i pre-particle filter equipped with a 47 mm, 5.0 μm MILLIPORE PTFE membrane filter. This filter effectively intercepts drifting snow grains and coarse aerosol particles under frequent blowing snow events at Antarctic Taishan Station and avoids pipeline blockage. Combined with the 2.9 m elevated layout of the intake port, the dual design greatly improves the environmental adaptability of the sampling system under harsh polar blowing-snow conditions.

Revision:

Revised Line No.: Lines 215–219 (3.1.1 Sampling)

Original: The intake port is also equipped with a particle filter to prevent the intake of snowflakes, dust, and other large particles that could contaminate the samples.

Revised: Furthermore, the inlet is installed with a Thermo-5030i pre-filter matched with a 47 mm-diameter, 5.0 μm MILLIPORE PTFE membrane filter. This filter can efficiently block blown snow particles and coarse dust, effectively avoiding pipeline clogging induced by frequent blowing snow in Antarctica and enhancing the environmental suitability of the sampling setup.

14. Lines 407–436: Replace "non-negligible defect" with "minor limitation" to conform to academic expression and make the statement more rigorous.

    Response: The expression is revised from non-negligible defect to minor limitation in Section5.1 as suggested for rigorous academic wording.

15. In the conclusions, the authors acknowledge that unattended polar observations still face common technical challenges, including temperature control precision, long-term energy supply, multi-parameter coordinated monitoring, and dynamic calibration. To ensure data continuity and completeness, the authors should propose further solutions for this observation system, rather than limiting the discussion to the one-month dataset.

    Response: We thank the reviewer for this valuable suggestion. We have supplemented targeted long-term improvement solutions for the four key technical challenges in the revised Conclusions section, beyond discussion of the one-month field measurement dataset, as detailed below:

    Optimization of temperature control & power consumption: Inspired by our previous discussion on heating schemes, follow-up upgrades will test the combination of self-limiting heating tapes plus aerogel thermal wrapping to implement intermittent intelligent temperature control, cutting continuous heating power without compromising thermal stability of internal instruments.

    Long-term energy supply improvement: Future deployment will adopt optimized PV-battery-methanol hybrid configuration to alleviate the power shortage risk during multi-month polar night.

    Multi-parameter coordinated monitoring: The next-generation CRUX-2.0 platform reserves modular expansion interfaces to sequentially add CH_4, H_2O and other trace gas sensors to realize synchronous multi-component atmospheric observation.

Dynamic automatic calibration upgrade: The existing single-point calibration limitation of CRUX-1.0 will be solved in CRUX-2.0. We have selected the ABB GLA131-GGA analyser after lab comparison against Picarro G4301; paired with multi-channel solenoid valves, this new configuration supports automatic multi-point standard gas calibration. CRUX-2.0 is currently undergoing field tests at Saishiteng Mountain (Lenghu, Qinghai), with trial completion scheduled for July.

16. References (Page 12 and thereafter): Inconsistencies exist in journal abbreviations, author names, and DOI formats. Please standardize them in accordance with AMT's reference format to ensure uniformity.

    Response: All reference items are rearranged following AMT official citation rules: unify journal standard abbreviations, author punctuation format and uniform DOI expression, eliminate formatting discrepancies across bibliography list.

17. Polish the language, split some overly long sentences (e.g., in the abstract and discussion sections), and revise a small number of non-native expressions to improve clarity and fluency.

    Response: Full-text language revision finished; split redundant lengthy compound sentences in Abstract, Introduction and Discussion; modify non-native English expressions to meet AMT writing standard and enhance readability.