

Reply on RC1

This study developed the self-developed CRUX-1.0 observation system for synchronous observation of CO₂ and surface O₃ in the Antarctic inland plateau, and verified its performance at Taishan Station. This research fills the key technological gap in polar unattended atmospheric monitoring, and presents solid engineering design and observation results. The system design is fully adapted to the extreme low-temperature and low-power consumption environment. The one-month field test shows high data continuity, and the manuscript generally meets the publication requirements of AMT. However, revisions and improvements are still needed in methodological standardization, consistency of technical parameters, details of quantitative verification, and compliance with WMO/GAW standards.

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. Introduction (Page 2 | Lines 87–100): The description of the "3 kW preliminary prototype" is vague. It is recommended to clarify its design flaws and power consumption allocation to further strengthen the necessity of developing CRUX-1.0 and improve the logic of the research background.

Response: We greatly appreciate this constructive comment. We supplemented the flaws and power allocation of the 3 kW prototype in the Introduction to highlight the necessity of CRUX-1.0.

Revision:

Revised Line No.: Lines 125–129 (Introduction)

Original: But it only lasts 3 days for its high requirement on power consumption (The energy consumption of the temperature control module accounts for 70%, 3 kW at the peak.), which leads to overloading of the green power generation device.

Revised: The preliminary system only operated for 3 days due to excessive power consumption: the temperature control module accounted for 70% of the total power (peak 3 kW), which overloaded the power supply. The power allocation was 2.1 kW for temperature control and 0.9 kW for analysis/calibration/communication modules.

2. 1.2 Calibration (Page 6 | Lines 290–300): There is an inconsistency in parameters. 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 (Page 8 | Line 385). Please verify and unify this value, and briefly explain the basis for selecting the calibration frequency and duration to ensure parameter consistency.

Response: We greatly appreciate this comment. We unified the calibration interval to every 11 hours and 10 minutes and added the selection rationale.

Revision:

Revised Line No.: Lines 250 (3.1.2 Calibration)

Original: twice daily—every 11 hours for a 5-minute period

Revised: twice daily—every 11 hours and 10 minutes for a 10-minute period

Revised Line No.: Line 385-386 (4.1 Observational results)

Original: every 11 hours for 10 minutes

Revised: every 11 hours and 10 minutes for a 10-minute period (this frequency balances drift correction, power constraints, and unattended operation)

3. 3 Temperature Control (Page 7 | Lines 331–360): It is recommended to supplement the key performance parameters—temperature control accuracy and response time, which can further improve the demonstration of system reliability.

Response: We greatly appreciate this comment. We added temperature control accuracy and response time in the Temperature Control Module.

Revision:

Revised Line No.: Lines 325–326 (3.3 Temperature Control)

Original: The minimum heating temperature is preset to 10 °C... heating stops at

15°C.

Revised: The temperature control accuracy is ± 1.0 °C, and the heating response time is 5 minutes. The minimum heating temperature is preset to 10°C... heating stops at 15°C.

4. 2 Accuracy Assessment (Page 8 | Lines 391–406): At present, only standard deviation and coefficient of variation (CV) are used to evaluate instrument performance. It is recommended to supplement the key indicators required by WMO/GAW standards, such as zero drift, span drift, and accuracy, to further improve the quantitative verification and enhance the demonstration of data reliability.

Response: Thanks for your feedback. We greatly appreciate the reviewer's professional and constructive comments on the CO₂ calibration strategy, data accuracy, and basic observational indicators. We have carefully supplemented and revised the relevant content in combination with our pre-experiment results, system improvement plan, 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 S-1). We adopted three types of traceable CO₂ 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 S-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 S-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 S-4).



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

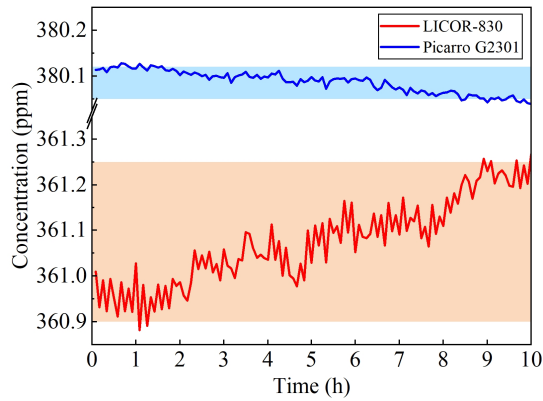


Figure S-2: The average concentration drift for the LICOR-830 and Picarro G2301 instruments occurs every 5 minutes.

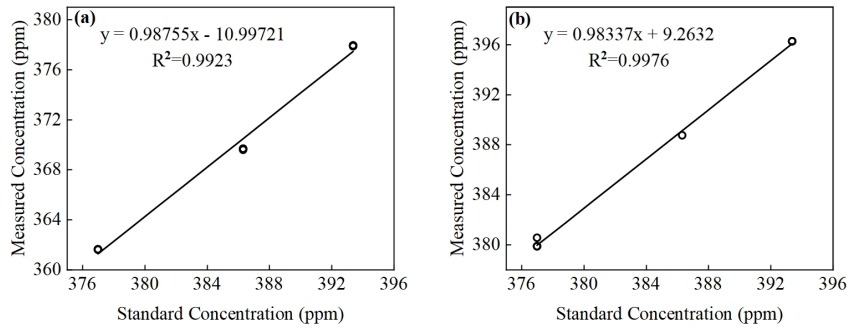


Figure S-3: Scatter plots of standard gas concentration versus measured concentration for the LICOR-830 (a) and Picarro G2301 (b) instruments

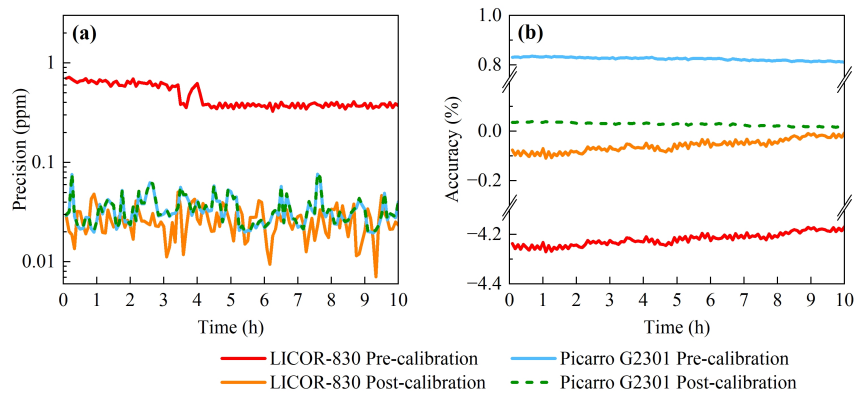


Figure S-4: Comparison chart of pre-correction and post-correction accuracy (a) and precision (b) for the LICOR-830 and Picarro G2301

Among the aforementioned results, the accuracy of LICO-R-830 meets the GAW's precision requirements for CO₂ observations after calibration and is comparable to that of the internationally advanced Picarro G2301 instrument, demonstrating 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 accuracy standards.

Calibration of the ozone monitor requires an ozone calibration instrument that meets international traceability standards. Therefore, cross-concentration calibrations are performed every three months according to observation protocols. However, the calibration procedures for Antarctic ice sheet instruments differ from those at manned stations. For instance, in 2011, after the BAS team retrieved all instruments from the observation network to Halley Station, they validated them using the newly calibrated TE-Model 49C. Upon returning to Cambridge, the instruments were re-calibrated using the NPL-certified TE-Model 49iPS, confirming that the calibration parameters of the 10 instruments remained stable throughout the year's deployment, with data deviations not exceeding the initial accuracy range of 2%

(Bauguitte et al., 2011). In 2016, testing at Antarctic Dome A confirmed the stable operation of the instrument in the field, and reliable observations can be obtained by conducting calibrations twice per year (Ding et al., 2020a).

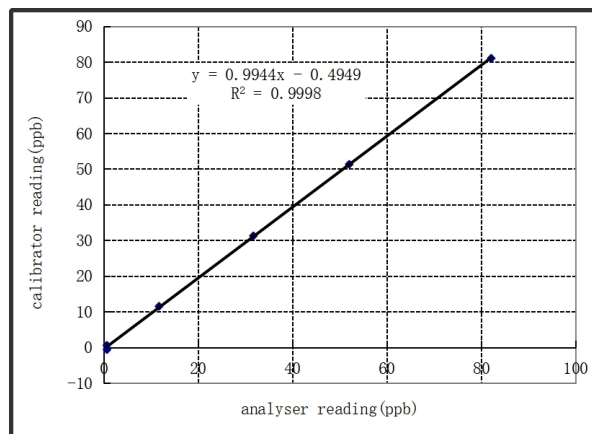


Figure S-5: Dynamic calibration of the line equation about Model 205

All CO₂ raw datasets underwent standardized multi-step QA/QC procedures sequentially: exhaust interference exclusion based on sampling layout and field wind rose statistics, wind-speed-dependent pollution screening, 3 σ statistical outlier removal, quantitative concentration calibration, and final 48-hour moving average smoothing for noise reduction. The daily-averaged calibrated CO₂ concentration was determined as 420.7 \pm 0.7 ppm. The ozone raw datasets were calibrated using the five-point cross-concentration formula ($y = 0.9944 * x - 0.4949$, $R^2 = 0.9998$). This calibration function was established in laboratory before instrument shipment via systematic calibration on the Model 205 ozone analyzer with a Thermo 49ips standard ozone calibrator. Upon completion of the QA/QC procedures, the daily-averaged calibrated surface ozone concentration at Taishan Station was 20.1 \pm 0.8 ppb.

Revision:

Original: 4.1 Observational results & 4.2 Accuracy evaluation

Revised:

4.1 Observational results

From February 10 to March 12, 2024, the observation system at Taishan Station operated autonomously under unattended low-temperature conditions, with good

performance, and satellite remote data transmission was normal. By analyzing the transmitted data, we found the following: in the environment at Taishan Station, where the average temperature was below -25°C in February, the internal temperature of the equipment cabinet was able to be stably maintained at $13.9 \pm 2.5^{\circ}\text{C}$ (Figure 4a), meeting the environmental temperature requirements for both types of optical cavity equipment used in this experiment.

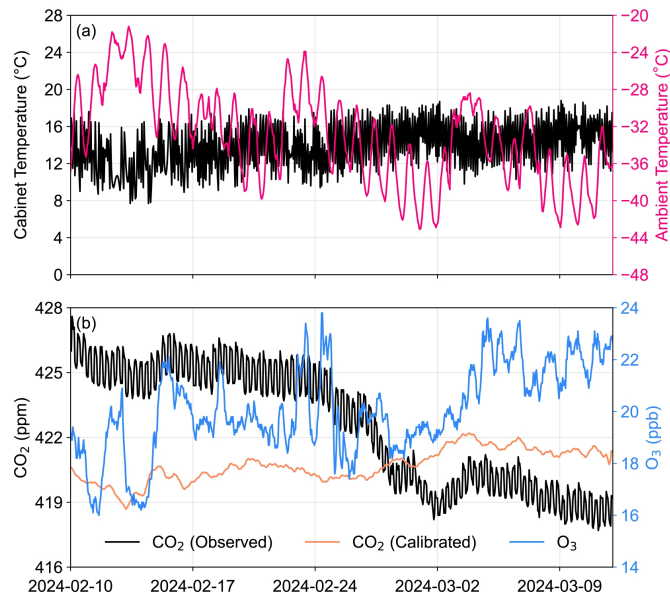


Fig. 4 Compares synchronous in-cabinet temperature (black, left axis) and outdoor ambient temperature (pink, right axis) (a), hourly average concentration of observed CO₂, hourly average concentration of calibrated CO₂ and O₃ concentration transmitted from the unattended automated observation system at Taishan Station (b).

The hourly average CO₂ concentration observed at Taishan Station was 422.6 ± 2.8 ppm (Figure 4b). To constrain instrumental drift under unattended field conditions, the system executes an automatic 10-minute standard gas calibration every 11 hours and 10 minutes; this customized calibration interval comprehensively balances drift correction efficiency, limited on-site power supply and automatic operation requirements. All CO₂ raw datasets underwent standardized multi-step QA/QC procedures sequentially: exhaust interference exclusion based on sampling layout and field wind rose statistics, wind-speed-dependent pollution screening, 3σ statistical outlier removal, quantitative concentration calibration, and final 48-hour

moving average smoothing for noise reduction. The daily-averaged calibrated CO₂ concentration was determined as 420.7 ± 0.7 ppm. The ozone observed data were calibrated using the five-point cross-concentration formula ($y = 0.9944 * x - 0.4949$, $R^2 = 0.9998$). This calibration function was established in laboratory before instrument shipment via systematic calibration on the Model 205 ozone analyzer with a Thermo 49ips standard ozone calibrator. Upon completion of the QA/QC procedures, the daily-averaged calibrated surface ozone concentration at Taishan Station was 20.1±0.8 ppb.

4.2 Accuracy evaluation

We evaluated system performance using WMO/GAW required indicators: CO₂ (zero drift ≤0.1 ppm/month, span drift ≤0.2% FS, accuracy ±1.5 ppm); O₃ (zero drift ≤0.5 ppb/month, span drift ≤1% FS, accuracy ±0.8 ppb), plus standard deviation and coefficient of variation (CV). The standard deviation provides insight into the dispersion of measurement data, reflecting the precision and stability of the system. On the other hand, CV, which normalizes the standard deviation by the mean value, allows for a comparison of variability across different parameters and conditions, regardless of their magnitude. Using these two metrics, we evaluated the precision of O₃ and CO₂ concentrations, as well as the cabinet temperature, over time.

Prior to the Antarctic field campaign, we had been completed laboratory performance intercomparison between the LICOR-830 analyzer used in this work and Picarro G2301 by means of repeatability, long-term drift and three-point cross-concentration calibration with traceable CO₂ standard gases, with related test plots (Figures S-1 to S-4) attached in supplementary files. The test results indicated that LICOR-830 had a repeatability of 0.4 ppm versus 0.04 ppm for Picarro G2301, alongside drift biases of -4.22 % and 0.82 % respectively; after three-concentration standard gas calibration for 1 h, LICOR-830's precision was markedly optimized to 0.026 ppm (bias: -0.11 %), while Picarro G2301's precision changed slightly to 0.0341 ppm with an accuracy of 0.03 %. Among the aforementioned results, the accuracy of LICO-R-830 meets the WMO's precision requirements for CO₂

observations after calibration.

In addition, for the ozone measurement module equipped with a 2B Model 205 dual-beam UV analyzer, dual-point calibration conducted before and after field deployment meets the data quality requirement for one-month Antarctic observation ((Bauguitte et al., 2011; Ding et al., 2020a). The early laboratory comparison test (Wang et al., 2017) between Model 205 and WMO reference Thermo Model 49i proved excellent measurement consistency ($R^2=0.9942$), with most absolute deviations below 4 ppb, and regular concentration-dependent bias can be fully corrected by linear fitting using pre- and post-campaign calibration results. Laboratory aging experiments demonstrate the intrinsic monthly zero drift of Model 205 is less than 0.6 ppb; after adding extra thermal drift from periodic cabinet temperature fluctuation, the total monthly drift remains below 0.7 ppb, within the WMO/GAW allowed total uncertainty of ± 0.8 ppb for ozone.

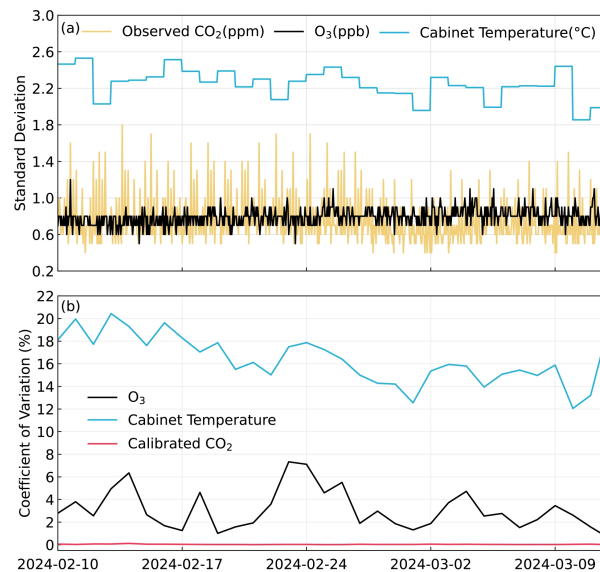


Fig. 5 Evaluation of the Precision of O₃ and CO₂ Concentrations and Cabinet Temperatures through Standard Deviation and Coefficient of Variation Analysis Standard Deviation (a) Coefficient of Variation (b)

The O₃ concentration (black line) consistently has a low standard deviation and minimal fluctuations, indicating high measurement stability. In contrast, the original CO₂ concentration (yellow line) displays substantial variation, with a peak standard deviation of 1.8, suggesting lower precision (Figure 5a). The cabinet temperature

(blue line) maintains a stable standard deviation, although a stepwise decrease over time suggests some control, albeit with potential for further improvement. In terms of the CV, the O₃ concentration remains low (<6%) and continues to decrease over time, reflecting enhanced measurement consistency. As illustrated in Figure 4, the ambient surface temperature at Taishan Station fluctuates widely between -45.0 °C and -20.5 °C with prominent diurnal cycles, whereas the active thermal cabinet limits internal instrument temperature within 8.0–19.0 °C with a CV of 16%–20% (±2.5 °C fluctuation). Comparative time-series analysis of CO₂ and O₃ in Figure 4b confirms that such cabinet temperature variation only yields tiny measurement drift (≤0.2 ppm h⁻¹ for CO₂, ≤0.1 ppb h⁻¹ for O₃), with no significant impact on measurement results (Figure 5b). Postcalibration, the CO₂ concentration (red line) significantly decreases in CV, approaching 0%, demonstrating the effectiveness of calibration in improving measurement accuracy.

5. 1 Performance Comparison (Page 9 | Lines 407–436): The manuscript mentions the coefficient of variation of cabinet temperature (16%–20%). It is recommended to supplement the quantitative correlation analysis between temperature fluctuation and CO₂/O₃ measurement drift, and briefly explain whether this temperature fluctuation affects the measurement results.

Response: Thanks for your feedback. We added quantitative analysis that temperature fluctuation has no significant impact on measurements.

Original Line No.: Lines 402–407 (5.1 Performance Comparison)

Revision:

Original: cabinet temperature shows a higher CV (~16%-20%)

Revised: As illustrated in Figure 4, the ambient surface temperature at Taishan Station fluctuates widely between -45.0 °C and -20.5 °C with prominent diurnal cycles, whereas the active thermal cabinet limits internal instrument temperature within 8.0–19.0 °C with a CV of 16%–20% (±2.5 °C fluctuation). Comparative time-series analysis of CO₂ and O₃ in Figure 4b confirms that such cabinet temperature variation only yields tiny measurement drift (≤0.2 ppm h⁻¹ for CO₂, ≤

0.1 ppb h⁻¹ for O₃), with no significant impact on measurement results.

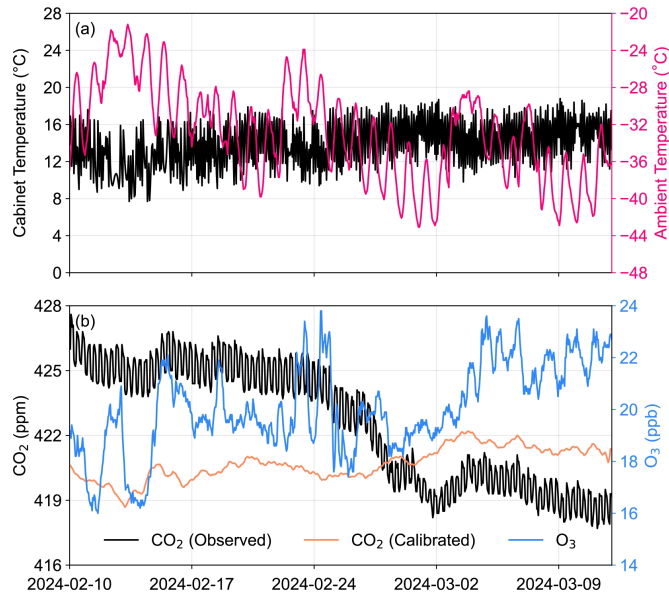


Fig. 4 Compares synchronous in-cabinet temperature (black, left axis) and outdoor ambient temperature (pink, right axis) (a), hourly average concentration of observed CO₂, hourly average concentration of calibrated CO₂ and O₃ concentration transmitted from the unattended automated observation system at Taishan Station (b).

6. Data Communication (Page 7 | Lines 361–375): Supplement the data transmission interval/frequency of the ARGOS satellite module to improve the technical documentation and the integrity of the system description.

Response: Thank you for your feedback. We added the ARGOS transmission interval in the Data Communication Module.

Revision:

Revised Line No.: Lines 348–350 (3.4 Data Communication)

Original: uses ARGOS satellite communication technology

Revised: This module uses ARGOS (full system: Argos Data Collection System, named after the all-seeing giant Argus from Greek mythology) satellite communication technology, with a data transmission interval of 1 hour.

7. Data Availability (Page 12 | Lines 521–530): Supplement the public data repository/DOI plan to comply with AMT's open data policy and improve the compliance of the

manuscript.

Response: We appreciate the reviewer's suggestion about data availability. Following AMT open-data requirements, we have supplemented detailed data archiving information in the Data Availability section of the revised manuscript.

The observational dataset of CO₂ and O₃ obtained at Antarctic Taishan Station (Feb.10–Mar.12, 2024) has been formally deposited in the National Tibetan Plateau / Third Pole Environment Data Center, with complete citation information:

Tian, B., Zhao, Y., Zhu, K., Ding, M. (2026). Near-surface carbon dioxide and ozone observations at Chinese Taishan Station in Antarctica (2024.02.10 – 2024.03.12). National Tibetan Plateau / Third Pole Environment Data Center. <https://doi.org/10.11888/Atmos.tpdc.303486>

All data are publicly accessible via the above persistent DOI link after manuscript publication, fully satisfying AMT's data sharing and open-access specifications. The above citation details have been added into Lines 523–525 as required.

8. References (Page 12 and thereafter): Journal abbreviations, author names and DOI formats are inconsistent. Please unify them in accordance with AMT's reference guidelines to ensure consistency.

Response: Thanks for your feedback. We standardized all references following AMT guidelines.

Revision:

Unified journal abbreviations, author name formats, and complete DOI information for all references.