CRUX-1.0: An automatic GHG and Ozone observation system for inland Antarctica Plateau

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Supplement material

1. QA/QC procedures

1.1 Impact of exhaust contamination

The sampling inlet is located 50 m due south of the generator cabin. Generator exhaust can only reach the inlet under northerly winds (337.5°–22.5°). Meteorological records show all wind directions during the campaign were 27°–119° (northeast/east/southeast), with no northerly wind observed (Figuer S1). In addtion, all measured wind speeds during the entire observation period were consistently higher than 3 m/s. No low-wind stagnant conditions with poor atmospheric dispersion appeared at any time and no prominent short-term concentration spikes were detected in the raw monitoring data. Thus, the impact of generator exhaust gases on monitoring data is negligible.

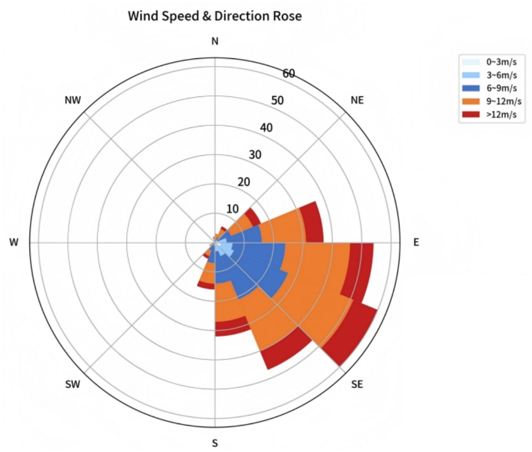

Fig. S1: Rose diagram of wind speed and direction during the trial period

1.2 Instrument calibration & drift correction

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 S2). 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 S3);

(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 S4), 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 S5).

Figure S2: Demonstration of the testing procedures using the LICOR-830 and Picarro G2301 instruments in the laboratory

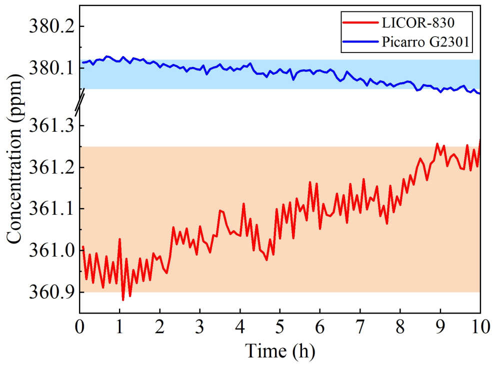

Figure S3: The average concentration drift for the LICOR-830 and Picarro G2301 instruments occurs every 5 minutes.

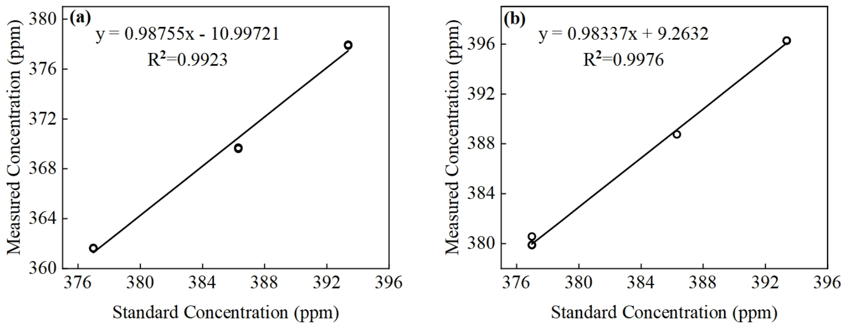

Figure S4: Scatter plots of standard gas concentration versus measured concentration for the LICOR-830 (a) and Picarro G2301 (b) instruments

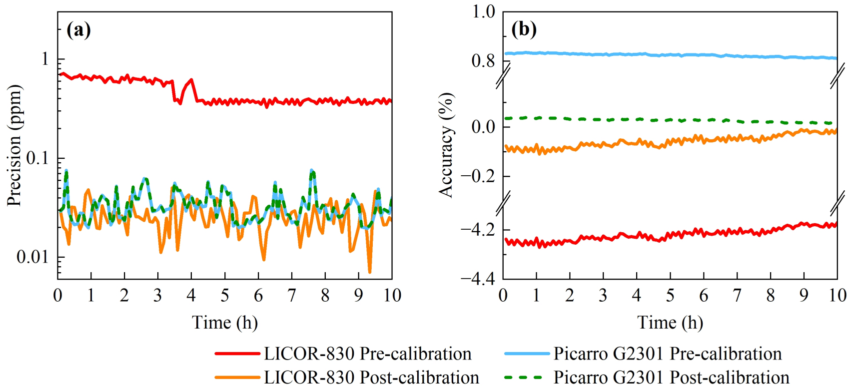

Figure S5: Comparison chart of pre-correction and post-correction accuracy (a) and precision (b) for the LICOR-830 and Picarro G2301

Among the aforementioned results, the accuracy of LICO-R-830 meets the GAW's precision requirements for CO_2 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).

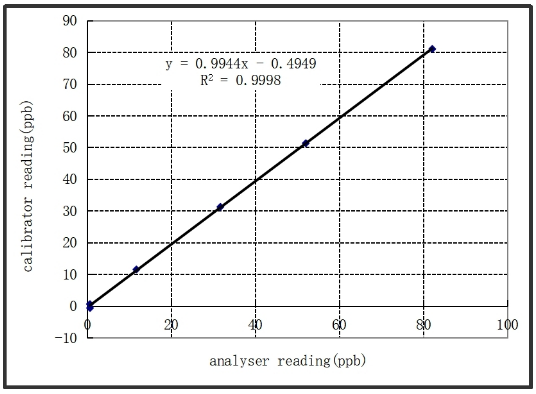

Figure S6: Dynamic calibration of the linearequation about Model 205

The daily-averaged calibrated CO_2 concentration was determined as 420.7 ± 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 (Figure S6). Upon completion of the QA/QC procedures, the daily-averaged calibrated surface ozone concentration at Taishan Station was 20.1±0.8 ppb.

2. Development of a long-term operation strategy

For long-term unattended high-precision observations, single-point calibration is insufficient, and this is a drawback of the current CRUX-1.0. To address this issue, we are currently carrying out system integration and field trials of the upgraded CRUX-2.0 system in Lenghu, Qinghai, and the trials are still ongoing. With the support of relevant instrument manufacturers, we conducted performance comparison tests on the low-power portable ABB GLA131-GGA analyzer and the low-power portable Picarro G4301 analyzer in the laboratory (Figure S7). The tests show that the accuracy of the ABB GLA131-GGA analyzer is significantly improved after multi-point concentration calibration, and it can meet the high-precision monitoring requirements of GAW after proper calibration. In addition, this instrument is equipped with an automatic sampling sequence control program, and when combined with a multi-channel solenoid valve box, it can realize autonomous timed calibration with multi-concentration standard gases. At present, the CRUX-2.0 system has been fully integrated and is undergoing field observation trials on Saishiteng Mountain, Qinghai.

For future long-term unattended high-precision observations, single-point calibration is insufficient, and we acknowledge that this is a limitation of the current CRUX-1.0 system. To address this issue, we are currently carrying out system integration and field trials of the upgraded CRUX-2.0 system in Lenghu, Qinghai, and the trials are still ongoing. We conducted a comprehensive performance comparison test between the low-power portable ABB GLA131-GGA analyzer and the low-power portable Picarro G4301 analyzer in the laboratory, covering repeatability, drift, and target standard gas calibration tests, with key results as follows:

Repeatability test: The ABB GLA131-GGA analyzer meets the WMO/GAW inter-site comparability targets for observation precision, achieving repeatability of $\pm 0.2\times10^{-6}$ for CO_2 and $\pm 2\times10^{-9}$ for CH_4 over a 300-second averaging period.

Drift test: The drift ranges of the GLA131-GGA analyzer in CO_2 and CH_4 measurements (0.28×10^{-6} and 0.72×10^{-9}, respectively) are superior to those of the Picarro G4301. The significant drift observed in the Picarro G4301 indicates limited reliability for long-term monitoring, requiring frequent calibration to maintain data accuracy.

Target standard gas test: After calibration, the relative error of CO_2 measurements by the GLA131-GGA analyzer decreased significantly from 1.86% to -0.03%, while the relative error of CH_4 measurements by the Picarro G4301 decreased from -0.39% to -0.15%.

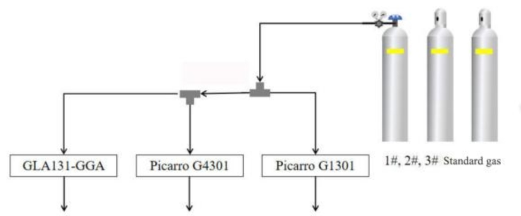

Figure S7: Schematic diagram of the experimental gas circuit connection and demonstration of the testing procedure

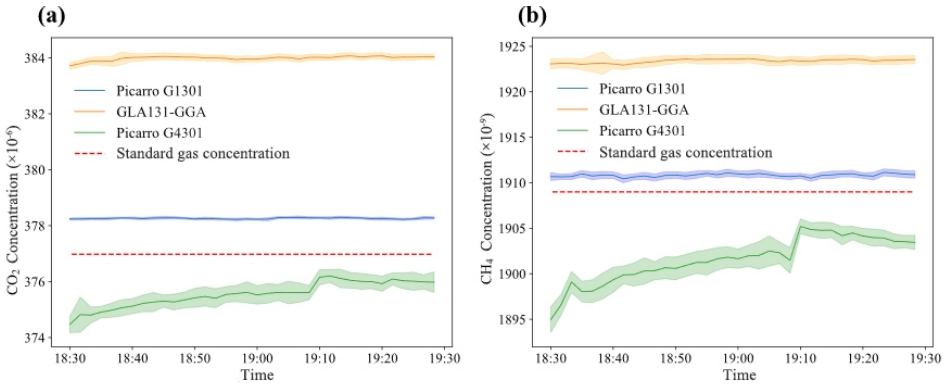

Figure S8: Average concentration values of measured CO_2 (a) and CH_4 (b) concentrations over 100-second intervals for the portable instrument

These results confirm that the accuracy of the ABB GLA131-GGA analyzer is significantly improved after multi-point concentration calibration, demonstrating its capability to meet the high-precision monitoring requirements of GAW with appropriate calibration. In addition, this analyzer is equipped with an automatic sampling sequence control program, and when paired with a multi-channel solenoid valve box, it can realize autonomous timed calibration using multiple concentrations of standard gases. At present, the CRUX-2.0 system has been integrated and is undergoing field observation trials on Saishiteng Mountain, Qinghai (Figure S9).

Figure S9: Field deployment of the integrated CRUX-2.0 system at Saishiteng Mountain

CRUX-1.0 relies on the fixed diesel power facility at Taishan Station. Its operation requires regular manual seasonal fuel refilling, accompanied by unstable power output and constrained energy reserve, which restricts long-duration observation. To overcome these drawbacks, CRUX-2.0 adopts a standalone PV-battery-methanol hybrid power system (Figure S10). Eight 200 W photovoltaic arrays together with 24 V lithium battery packs supply routine power and store surplus electricity, whereas the EMS automatically triggers the methanol generator to feed all system loads under overcast weather or polar-night darkness, removing frequent on-site refueling demands. We hope this design could engineered to sustain no less than three months of uninterrupted unattended operation.

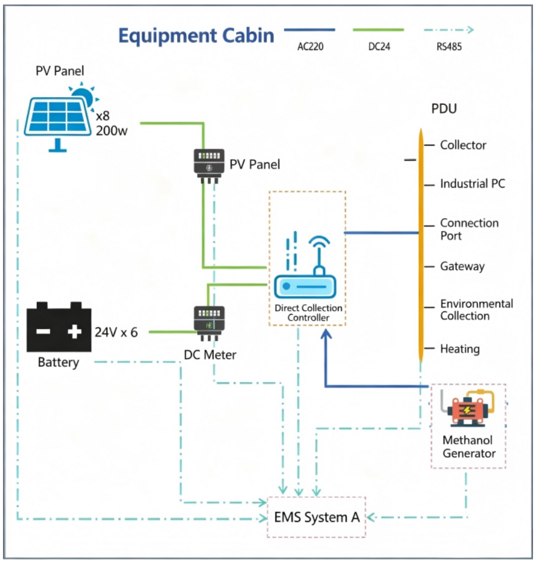

Figure S10: Schematic Diagram of Standalone PV-Battery-Methanol Hybrid Power Supply for CRUX-2.0