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

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Abstract: Antarctic inland regions, as critical hubs for global climate change monitoring, suffer from a lack of reliable long-term greenhouse gas (GHG) observation systems due to extreme low temperatures, strong winds, and limited logistical/energy support. To address this gap, the CRUX-1.0 automatic observation system was developed and deployed at Taishan Station (inland Antarctic Plateau) during the 39th and 40th CHINARE expeditions, targeting simultaneous monitoring of CO_2 and surface ozone (O_3). Integrating four core subsystems—analysis, calibration, temperature control, and data communication—the system is specifically engineered for harsh polar environments with low power consumption (<350 W) and autonomous operation capability. The operational analysis based on A one month continuous field experiment showed its stable performance: CO_2 measurements achieved a coefficient of variation (CV) <6% (nearing 0% post-calibration), while O_3 measurements maintained a CV <5.6%. The average concentrations (CO_2: 420.3±1.5 ppm; O_3: 20.1±0.8 ppb) closely aligned with regional background levels and South Pole Station data, confirming high reliability. With its robust adaptability, CRUX-1.0 could be extended to other polar or high-altitude regions, further enhancing the global atmospheric monitoring network's coverage and capability.

Keywords: GHG, Ozone, automatic observation system, Antarctica

1. Introduction

Observing atmospheric composition and greenhouse gases is a critical global issue, as it serves as a key benchmark for assessing global changes and formulating policies such as the Paris Agreement and Conference of the Parties (COP) negotiations. Currently, global atmospheric background stations provide a significant amount of observational data, but their distribution remains uneven. In fact, there are notable disparities in greenhouse gas concentrations across different regions.For example, high-latitude and polar regions, including Antarctica, suffer from a lack of observation stations, making it difficult to monitor the atmospheric composition in these

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

areas (Das et al., 2016; Liu et al., 2024). The absence of sufficient observation capacity in these regions highlights the need for enhanced monitoring systems. In particular, the challenging environmental conditions and logistical difficulties in these regions necessitate advancements in observation technologies and improved support for maintaining such systems. Given these challenges, there is a growing demand for increasing the capacity of remote, unattended observation systems to better capture the atmospheric background in these critical areas (Köne and Büke, 2010).

Autonomous and unattended atmospheric observation technology has achieved initial applications across multiple global spheres. Its core technologies (low-power hardware, automated quality control, and remote data transmission) provide a feasible solution for long-term monitoring in remote/extreme regions.In the marine boundary layer, the autonomous ozone measurement system (equipped with PSI and 2B Technologies sensors) developed by the Woods Hole Oceanographic Institution has successfully operated for over one month in an unattended mode on Atlantic buoys and the Chesapeake Bay Lighthouse Tower, thanks to its waterproof packaging, automatic valve protection (to cope with high winds and sea fog), and fault self-correcting controller. Among them, the 2B sensor consumes less than 4 W of power, which is compatible with the energy constraints of marine platforms (Hintsa et al., 2004). In the atmospheric background monitoring at fixed terrestrial stations, the 300-meter tall tower station in Bialystok, Poland, has implemented quasi-continuous observations of multiple species such as CO_2, O_2/N_2, and CH_4 since 2005. By automatically calibrating the CO_2/O_2 sensors every 40 hours, the gas chromatography module every 5 days, and conducting weekly flask sampling for quality control, the station has ensured data continuity for more than 3 years. Additionally, multi-height sampling has enabled effective differentiation between local and regional GHG signals (Popa et al., 2010). In the field of mobile observation, the MPAL vehicle-mounted monitoring platform of the University of Michigan achieves 6.5 hours of continuous operation of all instruments relying on $LiFeMnPO_4$ battery packs. Through automatic PM sampling loss correction and weekly comparison with fixed stations, it completed 84 days of observations with over 260,000 1-second resolution data points in Detroit, verifying the spatiotemporal coverage advantages of mobile unattended platforms (Xia et al., 2023). Furthermore, the REA-FTIR flux system at the Shoalhaven Farm in Australia completed 3 weeks of unattended simultaneous flux observations of CO_2, CH_4, and N_2O relying on 3G remote monitoring and automatic sampling bag switching, and also proposed an innovative method for estimating N_2O background fluxes via CO_2 tracer (Griffith et al., 2009).

The observation of greenhouse gases and other atmospheric components in Antarctica presents significant challenges, particularly regarding conducting unattended monitoring. The extreme environmental conditions, including low temperatures, strong winds, and long periods of darkness, pose technical difficulties for maintaining continuous observation systems (Griffiths et al., 2020). Moreover, logistical support in such a remote region is limited, making it hard to deploy and maintain equipment effectively. Over the years, targeted efforts have been made to address these challenges, with some advances in equipment adaptation, energy management, and data reliability: (1) British Antarctic Survey (BAS) Autonomous Ozone Network (2007–present): BAS deployed a network of 2B Technologies ozone monitors (ultraviolet photometry, 5 min sampling interval, 11–13 W power consumption) across 8 sites, from the southeastern coast of the Weddell Sea to the Antarctic Plateau (Bauguitte et al., 2011). The system relied on "solar-wind hybrid power + lead-acid batteries" (10–14 days of backup) and passive insulation with intake heating to avoid

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

icing. It delivered 5 years of continuous data (2007–2012), with spring ozone concentrations averaging 28±3 ppb along the coast (vs. 35±2 ppb on the plateau) and a data continuity rate of 85%. This work first confirmed that ozone depletion rates were higher at polar vortex edges (0.8 ppb/day) than inland (0.3 ppb/day). However, limitations emerged: passive insulation failed at -60°C (causing 15% winter data loss), wind turbine blade icing halted power supply for 12 consecutive days in 2009, and the lack of automatic calibration required manual on-site zero-checks, increasing operational costs (Bauguitte et al., 2011).

(2) Chinese Kunlun Station (Dome A) Ozone Monitoring (2016): During the 2016 Chinese National Antarctic Research Expedition (CHINARE), Ding et al. (2020a) deployed a 2B Technologies Model 205 ozone monitor (10 min sampling interval, 5 W power consumption) at Dome A (80.25°S), leveraging the PLATO astronomical observatory module's shared diesel generator and 50 kWh battery for power. The instrument operated continuously for 1 year, capturing the first annual ozone dataset for Antarctica's highest-latitude inland region—with polar night concentrations averaging 32±4 ppb and summer concentrations 29±2 ppb (15% lower than at Dome C). Data continuity reached 99.5%, validating the Model 205's suitability for extreme cold. Nevertheless, the system suffered from energy dependency (Ding et al., 2020a).

(3) Terra Nova Bay Station Stratospheric NO_2 Monitoring (2000): Bortoli et al. (2002) deployed a GASCOD UV-Visible spectrometer (423–460 nm wavelength, 0.5 nm resolution) at Terra Nova Bay Station for unattended NO_2 observations. Key adaptations included a 30° inclined quartz window to reduce snow accumulation, 24-hour continuous measurement (with integration time auto-adjusted from 2–5 seconds at noon to 5–10 minutes at twilight), and a built-in mercury lamp for daily grating calibration (spectral accuracy <0.2 nm). Invalid data were screened via the "Flux Index (FI)" (values $<5\times10^{-5}$ mV/ms rejected). The system yielded 1996 data showing NO_2 slant column densities (sc) dropping from 1.2×10^{17} to 4×10^{16} molecule/cm² in austral autumn and rebounding in spring—confirming coupling between photochemical loss and dynamic transport. It also quantified temperature-dependent errors: NO_2 sc increased by 3.5%–4% for every 10K rise in cross-section temperature. However, heavy snow in August 1996 covered the quartz window, causing a 7-day data gap, and mercury lamp intensity declined at -10°C, leading to two failed calibrations.

The Antarctic inland plateau faces unique challenges including ultra-low temperatures (below -40 °C), polar night (over 3 months without effective illumination), and extremely low logistical accessibility. Existing global unattended monitoring schemes (such as solar-powered supply for marine platforms, mains-powered calibration for terrestrial tall towers, and 3G communication for farmland systems) cannot be directly adapted to this region. Therefore, developing a fully automated greenhouse gases and surface ozone observation system tailored to the Antarctic inland plateau, which fills the gap in unattended monitoring of the atmospheric background in the polar inland, is of crucial significance for understanding the polar feedback of the global climate system. Building on these experiences, a new system to monitor greenhouse gases and surface ozone was developed in 2022/2023 and deployed at the Antarctic inland Taishan Station. 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. As a result, an improved system named CRUX-1.0 (The name "CRUX" is inspired by constellation of Crux is one of the most prominent and easily recognizable constellations in the southern hemisphere sky) was developed with 350 W power limitation and

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

tested at Tulihe, China, during cold season (- 20 to -40 ℃). Then in February 2024, it was deployed at Taishan Station on the Antarctic ice sheet. This system successfully operated for one month before the power supply broke down, providing valuable data on the atmospheric composition in this extreme environment. Here in this paper, we will introduce the detailed design of the system and its performance in Antarctica.

2 Site Descriptions

Atmospheric CO_2 and O_3 observational data in this study were obtained from one self-developed unattended monitoring system and four WMO-certified long-term monitoring stations with mature observation networks. The authoritative sources and verification channels for 2024 observational data are specified as follows: CO_2 data were retrieved from the World Data Centre for Greenhouse Gases (WDCGG) of the World Meteorological Organization/Global Atmosphere Watch (WMO/GAW, https://gaw.kishou.go.jp/data/), while surface ozone data were derived from the European Database for Atmospheric Sounding (EBAS, https://ebas-data.nilu.no/Pages/DataSetList.aspx). All datasets were verified via the WMO/GAW quality control system to ensure cross-station consistency and comparability (World Meteorological Organization [WMO], 2018; Montzka et al., 2015; Platt & Lunder, 2024).

2.1 Taishan Station

Taishan Station (72.01°S, 92.08°E; 2621 m a.s.l.) is located on the Antarctic ice sheet (Figure 1). It is situated on the high Antarctic Plateau, an area characterized by extreme environmental conditions. The station experiences strong katabatic winds and is positioned in a region with limited access to logistics and power resources, making it a challenging site for long-term atmospheric monitoring. The climate at Taishan Station is typical of the high Antarctic interior, where temperatures are consistently low throughout the year. The long-term data from September 2012 to July 2021 revealed an annual average air temperature of -35.4℃, with a relative humidity of 67%, an air pressure of 699 hPa, and an average wind speed of 10.9 m/s (Ding et al., 2022). The temperature exhibits significant seasonal variation, with a clear "coreless" winter, meaning that there is no distinct temperature minimum, which is common in the interior of Antarctica due to the unique seasonal sunlight patterns (Figure 2a, b, c, d). Furthermore, temperature variability is much greater during the austral winter (2.46℃) than during the austral summer (1.67℃), reflecting the greater frequency of weather events and atmospheric disturbances during the colder months (Ding et al., 2020b; 2022).

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

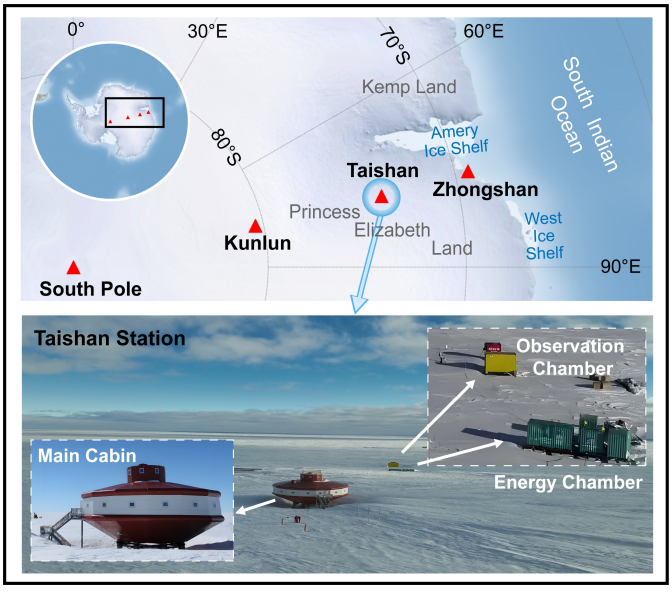

Fig. 1 Geographical distributions of Taishan station

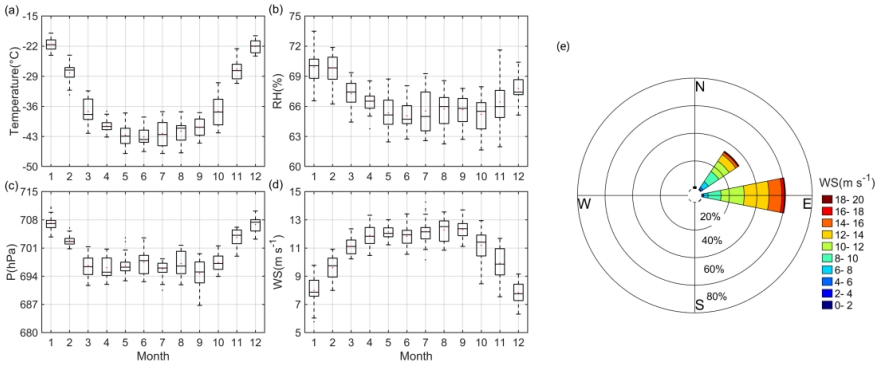

Fig. 2: Multiyear monthly average temperature (a), relative humidity (b), atmospheric pressure (c), wind speed, and wind direction (d, e) at Taishan Station.

In terms of wind patterns, Taishan Station predominantly experiences easterly winds throughout the year, with gusts reaching more than 20 m/s (Figure 2e). During the summer months, persistent easterly winds dominate the region, whereas in winter, the wind direction shifts from northeast to southeast due to katabatic forces, large-scale pressure gradients, and the Coriolis effect. These conditions contribute to significant challenges such as blowing snow, which can further affect a station's operations and observations (van den Broeke and van Lipzig, 2003; van den Broeke et al., 2002).

The CRUX-1.0 fully automated unattended observation system was deployed at Taishan Station from February 10 to March 9, 2024. This system has achieved simultaneous monitoring of CO_2 and O_3 and obtained continuous observation data. Specifically, the CRUX-1.0 system is installed in a yellow observation cabin, which is located approximately 100 meters to the southeast of the

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

green-colored unattended generator cabin (Figure 1). Given that easterly winds prevail at Taishan Station, the air inlet of the observation cabin is positioned on the upwind side of the generator cabin, which effectively minimizes the potential interference of the monitoring results from the exhaust emissions of the generator cabin. Detailed technical parameters and operational mechanisms of this system will be elaborated in Section 3.

2.2 Other Observation Stations

2.2.1 South Pole Station

Amundsen-Scott South Pole Station (SPO; 90°S, 24.8°W; 2837 m a.s.l.) is a manned baseline station located at the geographic South Pole, representing the coastal-inland transitional atmospheric conditions of Antarctica. Atmospheric CO_2 and O_3 are monitored using in-situ GC-MS and UV spectrometers with a 1-h sampling frequency, operated by the NOAA Global Monitoring Laboratory. Air samples are collected biweekly in paired glass flasks for offline verification, with weekly automatic calibration against NOAA-2016 standard scales (Montzka et al., 2015; Mahesh et al., 2003). The station's data continuity rate is 98.8%, and its observations are widely recognized as a benchmark for Antarctic coastal atmospheric background (Prinn et al., 2018).

2.2.2 Barrow Station

Barrow Station (BRW; 71.32°N, 156.61°W; 11 m a.s.l.), operated by NOAA's GMCC program, is a key Arctic coastal background station. The station monitors CO_2 and O_3 with NDIR analyzers and UV spectrometers at a 1-h temporal resolution, with additional flask sampling every 2 weeks for cross-validation. Affected by North American regional emissions and Arctic atmospheric circulation, BRW captures both baseline Arctic air masses and episodic pollution transport events (e.g., Eurasian arctic haze; Bodhaine et al., 1981). Data from BRW were averaged to 10-min intervals, with QC procedures following NOAA's standard protocols (Dutton et al., 2002).

2.2.3 Mauna Loa Station

Mauna Loa Station (MLO; 19.54°N, 155.58°W; 3397 m a.s.l.) is a global benchmark mid-latitude marine background station, operated by NOAA since 1958. Its CO_2 observations provide the longest continuous record of atmospheric greenhouse gas concentrations worldwide, with measurements conducted via hourly NDIR analysis and daily flask sampling. O_3 is monitored using UV absorption sensors with 1-h resolution, calibrated against WMO GAW standards. The station's remote location on the Hawaiian volcanic summit, dominated by westerly winds from the Pacific Ocean, minimizes local anthropogenic interference, making it ideal for capturing mid-latitude baseline atmospheric conditions (Keeling et al., 1976).

2.2.4 Jungfraujoch Station

Jungfraujoch Station (JFJ; 46.54°N, 7.96°E; 3580 m a.s.l.) is a high-altitude mid-latitude alpine background station in the Swiss Alps, managed by the ACTRIS network. It conducts in-situ monitoring of CO_2 (via Maihak broad-band infrared analyzers) and O_3 (via UV spectrometers) with a 6-min averaging frequency, supplemented by weekly flask sampling. The station is sensitive to European regional atmospheric circulation and photochemical activity, capturing distinct diurnal and seasonal fluctuations in trace gas concentrations (Kubistin et al., 2014). Data consistency is maintained through monthly cross-calibration with reference gas mixtures, with a long-term data completeness rate of ~92% (affected by alpine extreme weather; Sturm et al., 2012).

Despite minor calibration scale differences across networks (e.g., NOAA vs. ACTRIS), previous

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

studies have confirmed that inter-network biases are <1% for CO_2 and <3% for O_3, which are negligible for regional and global comparative analyses (Prinn et al., 2018; Wu et al., 2001).

3. Design of the observation system

The preliminary version of the unmanned automatic observation system, CRUX-1.0, is designed with 4 main modules: a sampling and calibration module, an analysis module, a temperature control module and a data communication module.

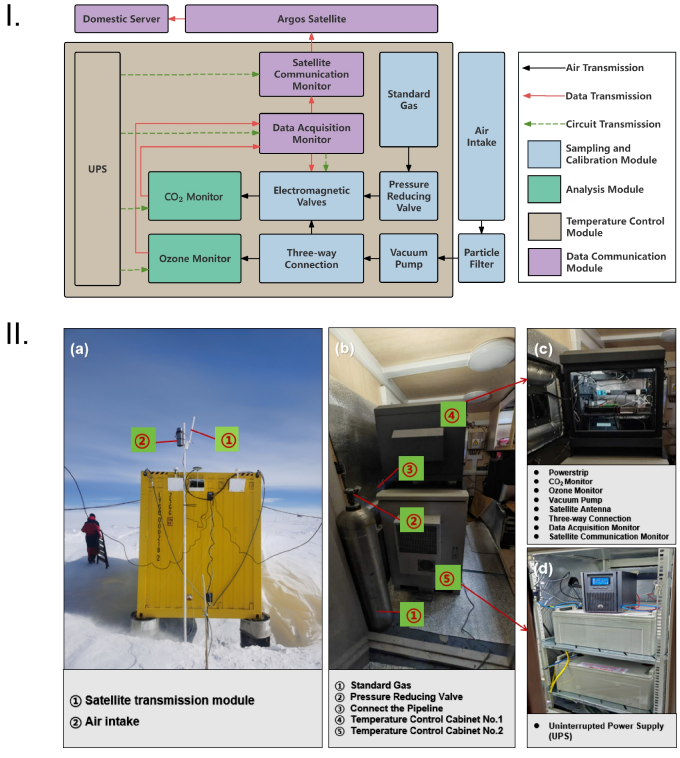

Fig. 3 Functional and structural layout (I) and onsite installation and layout (II) of the unmanned automated CO_2 and surface ozone observation system at Taishan Station

3.1 Sampling and Calibration Module

3.1.1 Sampling

The sampling module is responsible for collecting atmospheric gas samples and ensuring their consistent flow into the analysis module for evaluation (see Figure 3-I). It consists of several key components that work together to maintain a stable and reliable system. The intake port, positioned at a height of 2.9 m (see Figure 3-II-a), ensures that the air samples are representative of the surrounding atmosphere and not influenced by local pollutants or snow. 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. This elevated position and filter are crucial for ensuring that the collected data are as accurate as possible.

The gas flow controller, which includes a vacuum pump (Kamoer KZP-PE model: low rate ≥7 L/min; power≤12 W; positive pressure ≥0.2 MPa), standard gas cylinder pressure-reducing valve, and flow controller, ensures that the gas is drawn into the system at a constant rate (see Figure

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Preprint. Discussion started: 11 March 2026

3-II-b,c). The vacuum pump helps maintain a positive pressure airflow, whereas the flow controller regulates the gas flow for consistent sampling. Additionally, the system incorporates three-way and electromagnetic valves to allow the sampling system to switch between different sampling points or introduce calibration gases as needed. The overall design of the sampling module considers the dominant wind direction at Taishan Station, with the intake positioned in the upwind direction of the energy bin to minimize contamination from emissions. This thoughtful design ensures that the sampling module operates efficiently, even in harsh Antarctic environments.

3.1.2 Calibration

The calibration module is designed to eliminate instrument drift through standard gas calibration, ensuring the accuracy and stability of the observation data. The standard gas cylinder pressure-reducing valve controls the output pressure of the standard air, with the secondary gauge set to 1 psi. This setting ensures that the instrument's intake pressure is met while conserving the standard air as much as possible, thereby extending its usage duration. Each standard gas cylinder is certified for high precision and traceability and is equipped with a single-stage pressure-reducing valve. The cylinders are connected to the electromagnetic valve via 1/8-inch stainless steel tubing, ensuring the stability of the gas concentrations during transmission.

The electromagnetic valve is powered and controlled by the CR1000 data logger, which operates the valve at scheduled intervals through a prewritten control program. This program switches between external air and standard air intake, ensuring a consistent and controlled flow. To maintain a constant airflow through the instrument, a flow controller is installed downstream of the electromagnetic valve, preset to a constant flow rate. This ensures precise control over the gas flow entering the monitoring sensors, improving the accuracy of the measurements.

To prevent instrument drift from affecting the observation data, the system incorporates a standard gas calibration system, following the atmospheric background observation guidelines. The data logger sends instructions to the electromagnetic valve to allow standard air to flow into the system twice daily—every 11 hours for a 5-minute period. This calibration process ensures that the sensor is calibrated and that any drift is corrected while considering the limitations of energy consumption and the unmanned operating conditions at Taishan Station.

3.2 Analysis Module

3.2.1 CO_2 Monitor

To meet the energy consumption requirements at Taishan Station (where the atmospheric composition monitoring system needs to maintain a power consumption of less than 0.5 kW), a low-power LICOR-830 CO_2 analyzer (see Figure 3-II-c) is used in this experimental system. This device operates via the nondispersive infrared (NDIR) method, which consumes approximately 20 W of power. The NDIR method is considered one of the simplest yet effective technologies for gas detection because of its moderate sensitivity and fast response time. The LICOR-830 is widely used in various research fields, including agronomy, ecology, global carbon cycling, and climate change studies (Griffiths, 1983; Ekeberg, 2004; Chen et al., 2010).

The core components of the analyzer include an infrared light source, a light chamber, filters, and a detector. The working principle is as follows: infrared radiation emitted by the light source passes through the target gas in the light chamber. If the spectrum of the radiation overlaps with the absorption spectrum of the target gas, the gas absorbs photons at specific wavelengths according to the Beer–Lambert law (Kwon et al., 2009). After passing through the gas, the

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

infrared radiation is filtered so that only the wavelengths absorbed by the gas are retained. These specific photons, which contain concentration information, are detected by the sensor, and the signal is processed to display the concentration of the greenhouse gas (Xu et al., 2022).

Prior to deployment at Taishan Station, a preexpedition laboratory experiment was conducted to quantify the precision differences between the LICOR-830 and the Picarro G2301 greenhouse gas analyzers. This experiment aimed to assess the performance of observation systems based on different principles for measuring greenhouse gases (Nan et al., 2024). Through repeatability tests, drift tests, and target gas calibration tests, it was found that the accuracy of the LICOR-830, after calibration, met the WMO requirement of less than 0.1 ppm and was comparable to the advanced international accuracy level of the Picarro G2301, demonstrating its significant application potential in greenhouse gas monitoring.

3.2.2 Ozone Monitor

For ozone monitoring, a Model 205 ozone monitor from 2B Technologies (see Figure 3-II-c) was used in this experiment. This model was previously deployed in a year-long ground-based ozone observation experiment at Kunlun Station in Antarctica in 2016, where it successfully collected comprehensive observational data (Ding et al., 2022). Model 205 has demonstrated excellent applicability in ozone concentration monitoring, both domestically and internationally. It is energy efficient, highly accurate, compact, and lightweight, making it an ideal tool for monitoring atmospheric ozone concentrations in outdoor or field environments (Ollison et al., 2013; DiGangi et al., 2018; Tian et al., 2022).

The Model 205 ozone monitor operates via ultraviolet photometry (Williams et al., 2006). The ozone concentration was measured by detecting its maximum absorption at a UV wavelength of 253.7 nm. When an air sample enters the instrument's gas flow system at a constant flow rate, two electromagnetic valves alternate in directing the sample either into the absorption chamber or through an ozone filter before entering the absorption chamber. The absorption chamber concentrates stable UV light produced by the UV light source. Owing to the absorption characteristics of ozone at 254 nm, the intensity of transmitted light as the gas passes through the chamber is detected, providing accurate and stable measurements of the ozone concentration. Instruments based on this method are widely used in pollution monitoring, including atmospheric and water pollution (Tanimoto et al., 2006).

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). Owing to the overall energy consumption limitations and unattended conditions at Taishan Station, we conducted two calibrations, one before and one after the observation experiment, with data deviations not exceeding the initial accuracy range of 2%.

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

3.3 Temperature Control Module

The temperature control module is designed to ensure the stable operation of the monitoring equipment under extreme Antarctic conditions, especially the freezing temperatures at Taishan Station. This module includes a temperature control cabinet, a gas flow controller, and an uninterruptible power supply (UPS) (see Figure 3-II-b-④, ⑤). The temperature control cabinet is equipped with precise sensors and adjustment mechanisms that maintain a stable internal temperature range for the equipment, protecting it from extreme cold at the station.

To meet the appropriate temperature range for the operation of CO_2 and ozone monitoring while reducing the energy consumption of temperature control, the minimum heating temperature of the temperature control cabinet is preset to 10℃. When the internal temperature drops below 10℃, the system begins to heat; when the temperature exceeds 15℃, heating stops, ensuring that the equipment remains within a safe and optimal operating temperature range. This design ensures that the monitoring instruments are effectively protected in the extremely low-temperature environment of Taishan Station (which can reach as low as -40℃). The environmental monitoring and control system, which includes temperature regulation, is the highest power-consuming component in the entire system, with a peak power consumption of 250 W. Given the power constraints at Taishan Station, energy efficiency is a crucial consideration in the design of the temperature control system. This is balanced with the need to maintain a stable environment for the equipment.

Since the experimental system is powered by Taishan Station's external energy cabin, an uninterruptible power supply (UPS) system is installed to prevent sudden power outages or voltage instability from negatively impacting the system's operation (Figure 3-II-d). The UPS provides stable and reliable power to the entire monitoring system (see Figure 3-II-d). In the event of an external power failure, the UPS can quickly switch to backup power. The battery backup can last up to 48 hours, ensuring the continuous operation of the monitoring system and uninterrupted data collection. This design significantly enhances the system's reliability and fault tolerance, providing a safeguard against power disruptions in the remote environment.

3.4 Data Communication Module

The satellite communication system consists of a customized bracket (with a height of 3 m) and an integrated transmitting antenna (Figure 3-II-a-①), enabling high-speed and stable data transmission to a remote data center. This module uses ARGOS satellite communication technology, ensuring the real-time transmission of monitored data processed by the data logger in the harsh Antarctic environment, which can avoid potential interruptions and delays that could arise with traditional ground communication methods. The stable applicability of this satellite communication module in Antarctica has been verified through testing at the Prydz Bay-Amery Ice Shelf-Dome A (PANDA) profile automatic weather station (Ding et al., 2022).

The data processing and storage system uses the CR1000X measurement and control data logger (see Figure 3-II-c), a low-power device primarily used for sensor measurements, direct/remote communication connections, data analysis, external device control, and storage of data and programs. It features a sealed design to shield against radio frequency interference and a stainless steel housing. Equipped with a precise clock, it supports the BASIC-like programming language commonly used by Campbell Scientific data loggers, which includes data processing and analysis capabilities.

The CR1000X connection panel has two 12 V terminals, 16 analog measurement terminals, and

https://doi.org/10.5194/egusphere-2026-1227
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detachable connectors. It is responsible for receiving raw data from two monitoring sensors, performing preprocessing, analysis, and storage. This module has powerful data processing capabilities, enabling it to filter out and correct anomalous data points in real time, ensuring the reliability of the data quality. Additionally, the module supports remote data access and download functions, allowing researchers to retrieve and analyze monitoring data at any time.

4. Experimental analysis

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℃ in February, the internal temperature of the equipment cabinet was able to be stably maintained at 13.9 ± 2.5℃ (Figure 4a), meeting the environmental temperature requirements for both types of optical cavity equipment used in this experiment.

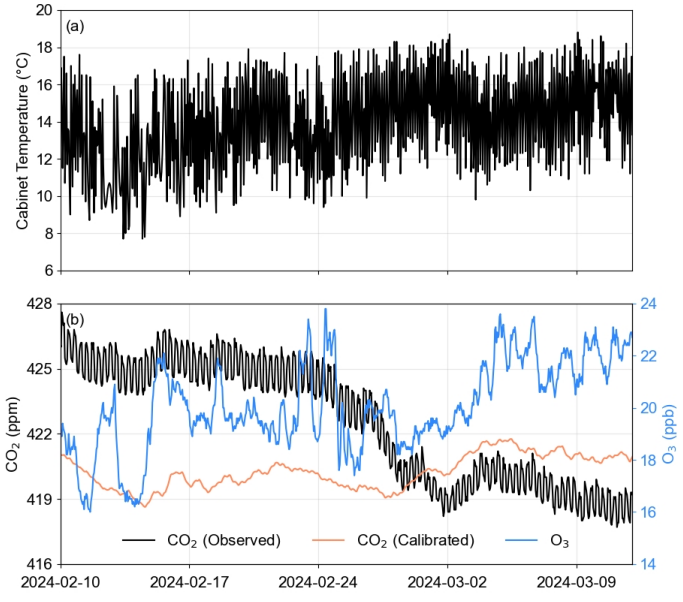

Fig. 4 Cabinet temperature (a), hourly average concentration of observed CO_2, hourly average concentration of calibrated CO_2 and O_3 concentration transmitted from the unattended automated observation system at Taishan Station (b).

From February 10 to March 12, 2024, the hourly average concentration of observed CO_2 at Taishan Station was 422.6 ± 2.8 ppm (Figure 4b). To ensure the accuracy of the observation data, the system automatically introduces standard gas every 11 hours for 10 minutes to correct the instrument measurement deviation. After data quality control, the daily average concentration of calibrated CO_2 at Taishan Station was 420.3 ± 1.5 ppm.

4.2 Accuracy evaluation

To assess the overall performance and stability of the system, we employed the standard deviation and coefficient of variation (CV) as key metrics. The standard deviation provides insight into the

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

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 O_3 and CO_2 concentrations, as well as the cabinet temperature, over time.

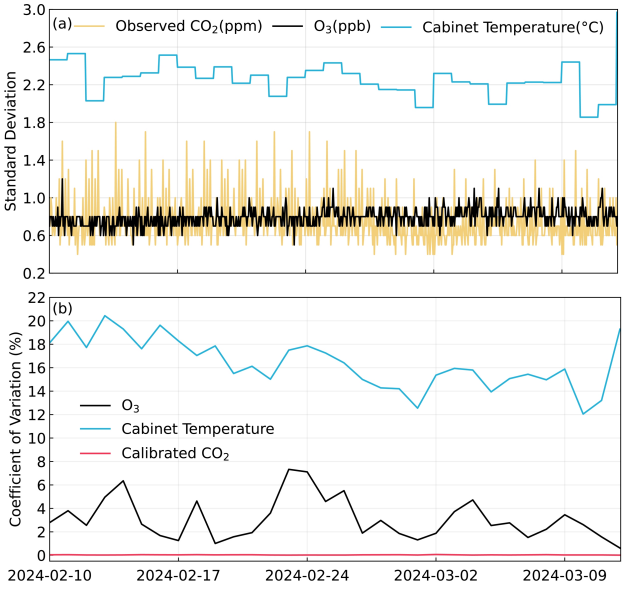

Fig. 5 Evaluation of the Precision of O_3 and CO_2 Concentrations and Cabinet Temperatures through Standard Deviation and Coefficient of Variation Analysis Standard Deviation (a) Coefficient of Variation (b)

The O_3 concentration (black line) consistently has a low standard deviation and minimal fluctuations, indicating high measurement stability. In contrast, the original CO_2 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 O_3 concentration remains low (<6%) and continues to decrease over time, reflecting enhanced measurement consistency. Postcalibration, the CO_2 concentration (red line) significantly decreases in CV, approaching 0%, demonstrating the effectiveness of calibration in improving measurement accuracy. However, the cabinet temperature shows a higher CV (~16%-20%), indicating notable fluctuations, possibly due to environmental factors or temperature control system design (Figure 5b). Overall, while O_3 concentration measurements demonstrate high precision and stability, CO_2 concentration precision improves substantially with calibration. Temperature control remains stable but requires optimization to reduce variability and further improve measurement accuracy.

5. Discussion

5.1 Performance Comparison

Traditional manned stations (e.g., South Pole Station) have irreplaceable advantages: real-time troubleshooting, flexible parameter adjustment, and weekly on-site calibration (measurement

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

uncertainty <0.5 ppm, better than CRUX's ±1.0 ppm for CO_2). However, manned observations face high logistics costs and data gaps due to extreme weather evacuations. CRUX compensates for these shortcomings: its 30-day autonomous operation cuts logistics costs by over 90%, and 48-hour UPS backup ensures data continuity during power outages. The consistency of its results with South Pole Station (CO_2: 420.3±1.5 ppm vs. 418.2 ppm; O_3: 20.1±0.8 ppb vs. 20.5 ppb) confirms it can provide comparable data quality in stable environments, serving as an effective supplement to manned observations.

Table 2. Comparison of the Polar Automatic GHG or Ozone Observation Systems

Key Techniques	CRUX-1.0 (2024)	BAS Ozone Network (2011)	Kunlun Station Ozone Monitor (2016)
Monitoring Parameters	CO_2 / O_3	O_3	O_3
Power Consumption	<350 W	11–13 W	5 W
Temperature Control Method	Auto-temperature control (10–15°C)	Passive Insulation with intake heater	Passive Insulation
Calibration Method	CO_2 : Automatic (Single standard gas mode, twice daily); O_3 : Periodic calibration	On-site zero-check with manual intervention and Periodic calibration	Periodic calibration
Single Battery Backup Duration	48 hours (UPS Backup Battery)	10–14 days (Lead-Acid Batteries)	Not applicable
Data Continuity Rate	99.2%	85% (Affected by power/communication)	99.5%

As shown in Table 2, CRUX's strengths lie in integrated optimization for Antarctic inland conditions: (1) Balanced performance: It reduces power consumption by 92% compared to the initial 3 kW version, achieving <350 W operation while maintaining multi-parameter detection, adapting to polar green energy constraints. (2) Extreme cold reliability: Active temperature control isolates -25°C to -40°C external temperatures, and upwind intake with particle filters mitigates blowing snow interference. (3) High autonomy and accuracy: Twice-daily auto-calibration reduces CO_2 CV to near 0%. Field tests revealed non-negligible flaws: (1) Temperature control lag: A 5-minute heating response delay leads to 16%–20% cabinet temperature CV, potentially causing 0.2 ppm/h drift of the LICOR-830 analyzer. (2) Insufficient long-term power: 48-hour UPS backup. (3) Limited adaptability: Fixed-time calibration cannot respond to sudden sensor drift; only two parameters are monitored.

5.2 Site Comparison

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

To interpret the observational results from Antarctic Taishan Station in a global context and assess the performance of the CRUX-1.0 unattended system, a comparative analysis was conducted on concurrent CO_2 and O_3 datasets from five global atmospheric background stations, which differ in geographical locations (polar vs. mid-latitude) and operational modes (unattended vs. manned). The selected stations include Taishan Station (Antarctic inland, unattended), South Pole Station (Antarctic coastal, manned), Barrow Station (Arctic coastal, manned), Mauna Loa Station (mid-latitude marine, manned), and Jungfraujoch Station (mid-latitude alpine, manned) (Figure 6a).

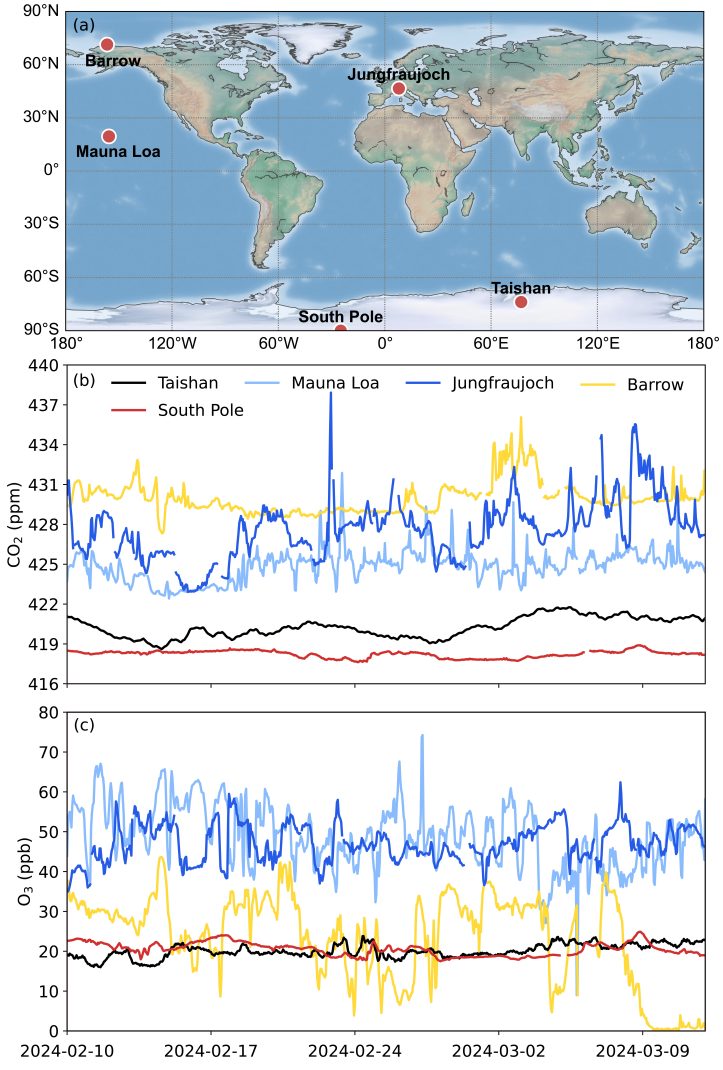

Fig. 6 Global distribution of selected atmospheric background stations (a) and their concurrent CO_2 (b) and O_3 (c) observations (2024-02-10 to 2024-03-12)

Comparative results revealed distinct regional and operational differences in both CO_2 and O_3 observations. For CO_2, polar stations (Taishan and South Pole; mean: 420.2 and 418.2 ppm;

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

hereafter means) exhibited significantly lower baseline concentrations than mid-latitude counterparts (Mauna Loa: 424.9 ppm; Jungfraujoch: 427.6 ppm), primarily due to the absence of anthropogenic emissions in the Antarctic inland. Taishan Station also showed smaller fluctuation amplitude (±1.5 ppm), attributed to the homogeneous air masses in the Antarctic inland circulation and interference-free operation of the unattended system, whereas mid-latitude stations displayed larger fluctuations driven by regional emission transport and diurnal cycles. For O_3, polar stations (Taishan: 20.1 ppb; South Pole: 20.5 ppb) had much lower concentrations than mid-latitude stations (Mauna Loa: 48.9 ppb; Jungfraujoch: 47.1 ppb), which was associated with weak photochemical activity in the Antarctic late summer., which was associated with the low concentrations of ozone precursors in Antarctica (due to the dual scarcity of natural and anthropogenic sources) impair the ozone formation potential, while the intense sunlight in summer, chemical depletion triggered by trace amounts of NO, and stable boundary layer conditions jointly lead to surface ozone in Antarctica being dominated by depletion during summer (Tian et al., 2022).

Notably, the data continuity rate of Taishan Station (99.2%) was comparable to that of the manned South Pole Station (98.8%), verifying the reliability of the CRUX-1.0 system in extreme polar environments. While mid-latitude manned stations excel in real-time calibration and multi-parameter expansion, the unattended CRUX-1.0 system fills the observation gap in the remote Antarctic inland, complementing the global atmospheric background network. Future optimization could integrate multi-point span calibration techniques from manned stations to enhance automated quality control.

6. Summary

To explore a new unattended observation model suitable for monitoring greenhouse gases (GHG) and surface ozone (O_3) in the extreme environment of the Antarctic inland plateau, this study developed the CRUX-1.0 fully automated unattended observation system. Integrating four core modules—sampling and calibration, analysis, temperature control, and data communication—the system is specifically optimized for polar conditions, featuring key characteristics such as low power consumption (<350 W), active temperature control (10–15°C), twice-daily automatic calibration for CO_2, and 48-hour uninterruptible power supply (UPS) backup. It is adaptable to observation needs in remote areas with low logistical support.

Deployed and operated at Taishan Station (72.01°S, 92.08°E) from February 10 to March 9, 2024, the system ran stably for one month with a data continuity rate of 99.2%. The calibrated CO_2 concentration was 420.3±1.5 ppm, and the O_3 concentration was 20.1±0.8 ppb, which were highly consistent with the concurrent manned observation results at South Pole Station. After calibration, the coefficient of variation (CV) for CO_2 was near 0%, and for O_3 was <5.6%, successfully verifying the reliability and feasibility of the unattended model for observations in extreme polar environments.

Compared with traditional manned stations, CRUX-1.0 achieves observation data of comparable accuracy at less than 90% of the logistical costs, providing a flexible and complementary new technical solution for the global polar observation network and facilitating the development of polar atmospheric background monitoring towards low-cost and wide-coverage. Currently, polar unattended observations still face common technical challenges, including temperature control precision, long-term energy supply, multi-parameter simultaneous monitoring, and dynamic calibration. In the future, joint efforts from academia and industry are urgently needed: promoting

https://doi.org/10.5194/egusphere-2026-1227
Preprint. Discussion started: 11 March 2026

the precision development of temperature control technologies for ultra-cold environments, exploring solar-wind-energy storage integrated hybrid energy systems for polar regions, developing multi-component collaborative observation modules and intelligent dynamic calibration algorithms, and further enhancing the extreme adaptability and observational comprehensiveness of unattended systems. This will provide more abundant polar atmospheric background data support for global climate change research.

Data availability

The in-situ observational datasets generated in this study, including the hourly raw and calibrated CO_2 and O_3 concentration data from the CRUX-1.0 system at Taishan Station, Antarctica, the system operation and temperature control records, and the data quality control results, are available from the corresponding author upon reasonable request. The reference CO_2 datasets for global background stations were retrieved from the World Data Centre for Greenhouse Gases (WDCGG) of WMO/GAW (https://gaw.kishou.go.jp/data/), and the surface ozone datasets were obtained from the European Database for Atmospheric Sounding (EBAS, https://ebas-data.nilu.no/Pages/DataSetList.aspx). Both public datasets are accessible in compliance with their respective official data policies.

Author contributions

Biao Tian was responsible for funding acquisition, field experiment, writing of the original draft, experimental design, and formal analysis. Minghu Ding was responsible for project administration, supervision, resources coordination, and review and editing. Kongju Zhu and Xu Yao were responsible for on-site field experiment. Yixi Zhao was responsible for formal analysis and data visualization. Wenqian Zhang was responsible for system software debugging and remote data acquisition. Diyi Yang, Weijun Sun, Yining Yu, Shoudong Zhao, Yige Cui, Chuanjin Li, Jie Tang, Cunde Xiao, Tong Zhu, and Renhe Zhang were responsible for review and editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Preprint. Discussion started: 11 March 2026

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