Development and application of the Ascent-Drift-Descent Radiosonde System (ADDRS)

Xiaozhong Cao[1], Qiyun Guo[2,3,4], Haowen Luo[2,3,4], Rongkang Yang[2,3,4], Peng Zhang[2,3,4], Guo Jianping[5], Jincheng Wang[6], Die Xiao[7], Yinfeng Liu[8], Zhongliang Sun[9], Shijun Liu[10], Sijie Chen[11], Anfan Huang[2,3,4]

[1] China Meteorological Administration, Beijing, China;

[2] Meteorological Observation Centre of China Meteorological Administration, Beijing, China;

[3] State Key Laboratory of Environment Characteristics and Effects for Near-space, Beijing, China;

[4] Engineering Technology Research Center for Meteorological Observation of CMA, Beijing, China;

[5] Chinese Academy of Meteorological Sciences, Beijing, China;

[6] CMA Earth System Modeling and Prediction Centre (CEMC), Beijing, China；

[7] Hunan Key Laboratory of Near-space Meteo-ballon Materials and Technology, Zhuzhou Research & Design Institute Co, Ltd, Zhuzhou, China;

[8] Beijing Huayun Orient Detection Technology Co, Ltd.,Beijing, China;

[9] Allystar Technology (Shenzhen) Co.LTD. , Shenzhen, China;

[10] Department of Advanced Technology Training of China Meteorological Administration, Beijing, China;

[11] National Satellite Meteorological Centre of China Meteorological Administration, Beijing, China;

Corresponding author: Xiaozhong Cao, caoxzh@cma.gov.cn

ABSTRACT. The balloon-borne radiosonde observations constitutes a crucial component of meteorological sounding, which conducts a ground to uppe-air “ascent phase” sounding. This paper introduces the Ascent-Drift-Descent Radiosonde System (ADDRS), an innovative system characterized by three observation phases—'Ascent-Drift-Descent' (ADD)—in which all three phases of sounding observation are executed through single balloon launch. Several key technologies were successfully developed, including the carrier (dual-mode balloon), the payload (System-on-Chip (SoC) module for meteorological sounding), Ground to upper-air data reception and control command transmission and data processing framework based on 'Internet cloud + Instrument terminal' was established. Data quality control methods and data assimilation techniques of ADDRS were also developed. An interactive experiment encompassing observations and forecasting was conducted to evaluate the quality of experimental data at each phase of ADDRS. A numerical experiment on the impact of ADDRS data assimilation on forecasting demonstrated a 2% reduction in precipitation forecast error at 06:00 and 18:00 (UTC), along with an average 1% improvement in precipitation forecast accuracy following the assimilation of ADDRS data. Furthermore, a new trajectory prediction method for ADDRS, achieved an average simulated landing-point error of less than 40 km. Notably, the accuracy of first guess positioning and trajectory prediction for Typhoon 'Saola' in 2023 was significantly enhanced through ADDRS data assimilation, reducing the average trajectory prediction error by 40%. On January 1, 2024, operational observations using ADDRS commenced at four radiosonde observations stations in Guangdong, China. Starting in July 2024, an operational experiment at one hundred and twenty-seven stations within the China Meteorological Administration (CMA) was operation over one year, which will achieve full operational capability by 2026.

1. Introduction

The upper-air meteorological sounding system (hereinafter referred to as 'sounding') constitutes a key element within comprehensive meteorological measurement framework (Ingleby and Coauthors., 2016). It is responsible for gathering data on various meteorological elements such as temperature, humidity, pressure, wind speed, and wind direction from the surface up to heights of 30 km and beyond upper atmosphere (DuBois et al., 2002). This system provides vertically observed meteorological data for weather forecasting, numerical weather prediction, climate projection, scientific research, and the inspection and calibration of ground-based remote sensing equipment (Seidel et al., 2009; Fujiwara et al., 2025). The integration of radiosonde technology with balloon-borne soundings emerged in the 1930s, with early operational systems deployed in the 1940s; this technology has since served as a primary tool for direct measurements of upper-air meteorological elements below 30 km and is widely utilized on a global scale (Pettifer 2009; Gallice et al., 2011).

For nearly a century, these radiosondes have utilized the direct measurement method of “one balloon launched, one profile”. Where the radiosonde ascends at a certain speed with the balloon expanding in volume due to decreasing air pressure as altitude increases. Upon reaching a specific altitude, the balloon bursts, concluding the measurement process. This methodology confines effective observations to the radiosonde's ascent phase (Haig et al., 1958). The disposable nature of radiosondes and balloons necessitates significant costs for multiple deployments. Consequently, economic constraints have led to reductions in sounding operations, such as Russia's temporary reduction of launches from twice to once daily in 2015, impacting the forecasting accuracy of numerical prediction models across Northern Hemisphere countries (Ingleby et al., 2016).

Currently, the radiosonde observations are still very useful for validation/verification satellite observations (Bauer et al.,2015; Bormann et al.,2019; WMO et al.,2024). But the temporal resolution of global radiosonde observations data remains limited, posing a significant challenge to its capacity in fulfilling the requirements of routine forecasting. A notable concern arises from the scarcity of direct measurement data during periods characterized by frequent severe convective activity, particularly in the hours immediately following noon. Numerous studies have demonstrated that the frequent acquisition of descent radiosonde data can significantly enhance the accuracy of numerical weather forecasting. The ECMWF reported about successfully assimilating radiosonde descent data from ships (Ingleby, 2021), And the United States and other nations have successfully assimilated airborne radiosonde data into their model systems, leading to a 10–15% reduction in errors associated with hurricane trajectory predictions, particularly over oceanic regions where data is sparse (Cohn et al., 2013; Wang et al., 2015).

Additionally, numerous institutions are actively investigating techniques to obtain multiple radiosonde data points from a solitary balloon launch. Illustrative projects include the multidisciplinary analysis of the African monsoon and the measurement system research and forecasting experiments conducted in the Asia-Pacific region, which utilize balloons to conduct drop soundings as they drift with stable upper-air winds over the ocean (Raman et al., 2011). The WindBorne emerged in 2019 from the cradle of the Stanford Space Program . Once launched, the WindBorne balloon regulates its altitude by jettisoning sand ballast and releasing gas, enabling multiple round-trip vertical sounding flights from below 20 km down to near the surface, with an average flight duration of seven days (Johnson, 2024). Similarly, the French Space Agency, CNES, has developed an Super Pressure Balloon (SPB) capable of floating in the stratosphere for over three months (Roth et al., 2022). Additionally, the Tata Institute of Fundamental Research Balloon Facility (TIFR-BF) in India has

also contributed to this field by developing comparable systems (Anand et al., 2021; Vernier et al., 2018; Vernier., 2022). The systems delineated in these studies are primarily used for scientific experiments. Nonetheless, due to high costs and limited ascent rates, they are not viable solutions for long-term operational balloon sounding data collection. Furthermore, these balloons very slow ascent rates (necessary for managing factors such as heat dissipation, ventilation, and sensor response times) do not meet WMO standards for balloon ascent speed (WMO-No. 8., 2025).

Another conducted an extensive analysis by compiling four years of radiosonde data collected without parachutes across various seasons and altitudes, highlighting the scientific value of descent data (Ratnam et al., 2014; Ingleby et al., 2022). On account of the sounding process of ascending and descending at the same station has restricted its potential in conducting adaptive or targeting observation on typhoon forecast (Tan et al., 2006). This paper introduce a new sounding technology—the Ascent-Drift-Descent Radiosonde System (ADDRS). This system can improve the spatial and temporal frequency of soundings and provides an additional vertical profile as well as maintaining cost-effective, which acquires radiosonde measurement data throughout three phases—'Ascent-Drift-Descent' (ADD)—all within a single balloon launch (Cao et al., 2019).

2. Synopsis of the Ascent-Drift-Descent Radiosonde System (ADDRS)

The ADDRS was organizational developed by the Meteorological Observation Centre of the China Meteorological Administration (MOC of CMA) with other relevant domestic units in China (hereinafter referred to as the 'ADDRS research team'). It undertakes a three-phase Round-trip upper-air measurement (Fig. 1). In addition to the ascent phase of the current sounding system, ADDRS enables sounding during both the drift and descent phases. This innovative approach completes three phases of sounding with only a single balloon launch, representing a significant advancement in comparison with the traditional upper-air sounding method that has been utilized for nearly a century (Cao et al., 2022).

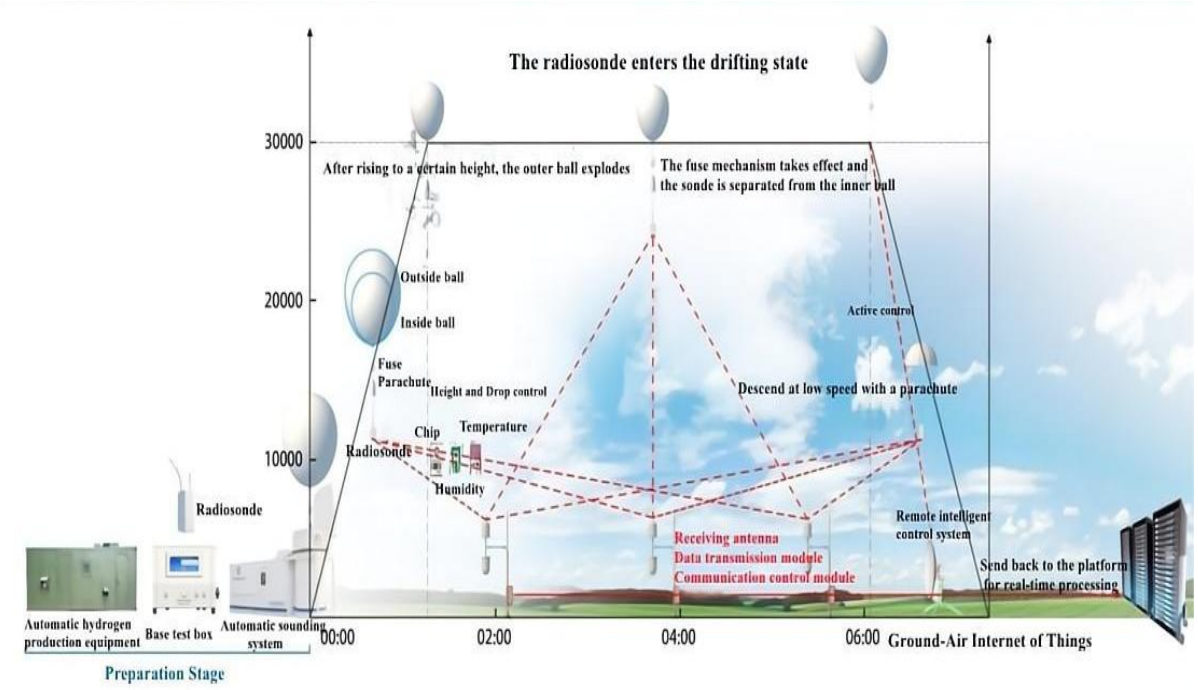


Figure 1. Operational principle diagram of the Ascent-Drift-Descent Radiosonde System (ADDRS).

Table 1. Main instruments and key functions of ADDRS.

No	Subsystem	Instruments	Key Function
1	"ADD" subsystem	dual-mode balloon	"outer balloon"as ascent carrier， "inner balloon" as drift carrier
2		parachute	parachute as the carrier of the descent phase
3		drifting controller	Adaptive control of drift and descent
4		radiosonde	The temperature, pressure, humidity, wind measurement meet the demand for long-term stratospheric observation
5	Ground operation control subsystem	Ground station	ground inspection ground check, balloon inflation, launch, and other tasks before the equipment is launched
6		Multichannel sounding receiver	8 channels receive radiosonde data simultaneously
7		control command transmitter	In the weather-sensitive area without a station, the active fusing drifting controller is carried out and the descent measurement is started
8		operational management system	Real-time acquisition, transmission, quality control, and timely delivery of control instructions for ADDRS data, providing real-time high-quality data to weather analysis and numerical prediction models

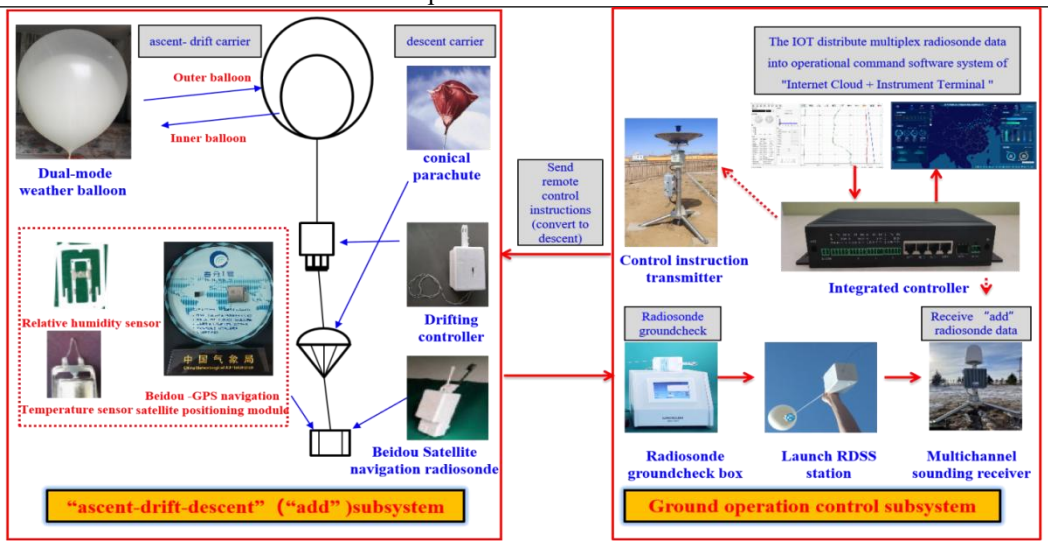


Figure 2. Schematic representation of the equipment composition for ADDRS.

The ADDRS primarily consists of the 'ADD' subsystem and the ground operational control subsystem, as shown in Table 1 and Fig. 2. The 'ADD' subsystem encompasses a dual-mode balloon with a parachute, a drifting controller, and a radiosonde. The dual-mode balloon features a design where one balloon embedded within another, both made from a latex material similar to that of operational meteorological sounding balloons and filled with hydrogen. Upon inflation and launch of the dual-mode balloon, the 'ADD' subsystem at a rate of ascent between 5 and 7 m/s (WMO-No. 8., 2025). As it rises, the external air pressure decreases, causing the balloon to expand. At the predetermined altitude (generally between 28km and 30km), the outer balloon bursts due to its expanding volume, marking the conclusion of the ascent phase measurement. Given that the outer balloon bursts within the stratosphere, where vertical air movement is minimal, horizontal movement becomes predominant. The enhanced performance and controlled aeration of the inner balloon enable it to resist bursting. At this juncture, the buoyancy of the inner balloon attains equilibrium with gravity, achieving an approximate

vertical stability. Subsequently, the inner balloon, primarily influenced by horizontal air currents, functions as the carrier for the drift phase, which initiates thereafter.

After drifting for a predefined duration, which may vary from a couple of hours to over ten hours, the drifting controller separates the inner balloon from the rest of the ADDRS equipment, thereby terminating the drift phase. Subsequent to this separation, the inner balloon persists in ascending until it ultimately ruptures, marking the conclusion of its mission segment. Meanwhile, the remaining components — comprising the parachute and radiosonde—begins to descend. The parachute is promptly deployed, facilitating the radiosonde in collecting data during the descent phase, while acting as its carrier. This descent persists until the equipment touches down, thereby completing the final phase of the 'ADD' process. At this point, ADDRS has successfully completed the three-phase 'Ascent-Drift-Descent' measurement.

The ground operation control subsystem of ADDRS comprises four main components: the balloon launch station, ground data-receiver (downlink communication), control command transmitter (uplink communication), and the operational management system. The balloon launch station is similar to existing meteorological radiosonde launch stations, undertaking tasks such as ground checks, balloon inflation, and launching the balloon with a radiosonde at scheduled intervals. Ground data-receiver can also be placed at the balloon launch station. However, its layout and function differ from operational-sounding data-receiving equipment. Due to the ADDRS drift phase, the horizontal distance between the descent point of the radiosonde and its launch point can exceed 500km, while operational radiosonde data reception has a maximum linear transmission distance of around 200km-300km. Therefore, the traditional single-station, point-to-point radio communication mode of radiosondes is inadequate for ADDRS data reception. Thus, the ground to upper-air communication system has been upgraded from point-to-point to a multiple-to-multiple model. In areas through which the radiosonde's ADD phases may pass, ground data-receivers are strategically deployed. This configuration enables multiple ground data-receivers to concurrently receive data from a single radiosonde or alternatively, a single receiver to capture data signals from several radiosondes simultaneously. Consequently, the ground data-receiver is designed as a P-band 8-channel parallel data receiver, capable of receiving data from multiple radiosondes simultaneously. Additionally, control command transmitters are located at the ground station and other locations. These transmitters send control instructions from the ground to the drifting controller in the air through uplink communication. This system allows for the adjustment of the drift phase elevation, termination of the drift phase, and switching to the descent phase measurement as needed.

The operational management system acts as the brain of the entire ADDRS system. Multiple ground data-receivers and control command transmitters are connected to the operational management system via the Internet. These ground data-receivers continuously transmit data to the operational management system in real-time for processing, display, and storage. Based on the ADDRS trajectory and specific weather and climate conditions, comprehensive decision-making allows the operational management system to transmit control instructions to control command transmitters which then relay them to the drifting controller in the air to execute the desired functions.

The 'Internet cloud + Instruments terminal' architecture enables real-time, efficient, and bidirectional communication across the entire network during the 'ADD' phases. This configuration supports the seamless real-time acquisition, transmission, and quality control of ADDRS data while ensuring rapid data delivery for

weather forecasting. Consequently, it enhances the timeliness and availability of radiosonde data for forecasting purposes.

3. Critical scientific problems

3.1. Carrier technology

Compared to using deflation in super-pressure balloons for drifting (Anand et al., 2021; Vernier et al., 2018; Vernier. et al., 2022), the dual-mode balloon structure of ADDRS is simpler, more cost-effective, and suitable for large-scale deployment in operational upper-air meteorological observations. The ideal 'ADD' process works as follows: the outer balloon provides lift and explodes after reaching a predefined altitude range. Subsequently, the inner balloon and its associated equipment achieve vertical equilibrium, enabling a stable drifting state. Therefore, while the ascent measurement of the balloon sounding is completed, achieving extended drift and controlled descent remains a technical challenge that ADDRS carriers aim to overcome.

3.1.1 Study on the influence of atmospheric environment on the net lift power of balloons

A multitude of meteorological factors, encompassing air temperature, air pressure, solar radiation, and other external environmental conditions, coupled with the gas volume of the outer balloon directly influences its net lift and burst altitude. Variations in air pressure and temperature within the outer balloon, induced by external meteorological conditions, interact with the expansion dynamics of the inner balloon. These factors, in conjunction with the aeration volume of the inner balloon, collectively influence the altitude during the drift phase and the static equilibrium of the inner balloon. Consequently, controlling the hydrogen inflation volume in the dual-mode balloon presents a significant challenge (Xu et al., 2025).

The ADDRS research team conducted an in-depth theoretical analysis of the ascent and drift processes of the dual-mode balloon, focusing on three areas: upper atmosphere model expansion, the balloon's dynamic equation, and a thermodynamic model. This study led to the development of a coupling model that accounts for the effects of atmospheric conditions on the balloon's net lift (from now on referred to as the "coupling model") (Liu, S. J et al., 2022). This model provides a theoretical foundation for determining the net lift force, ascent velocity, and target burst altitude of the dual-mode balloon, enabling precise control of aeration in the dual-mode balloon under varying meteorological conditions.

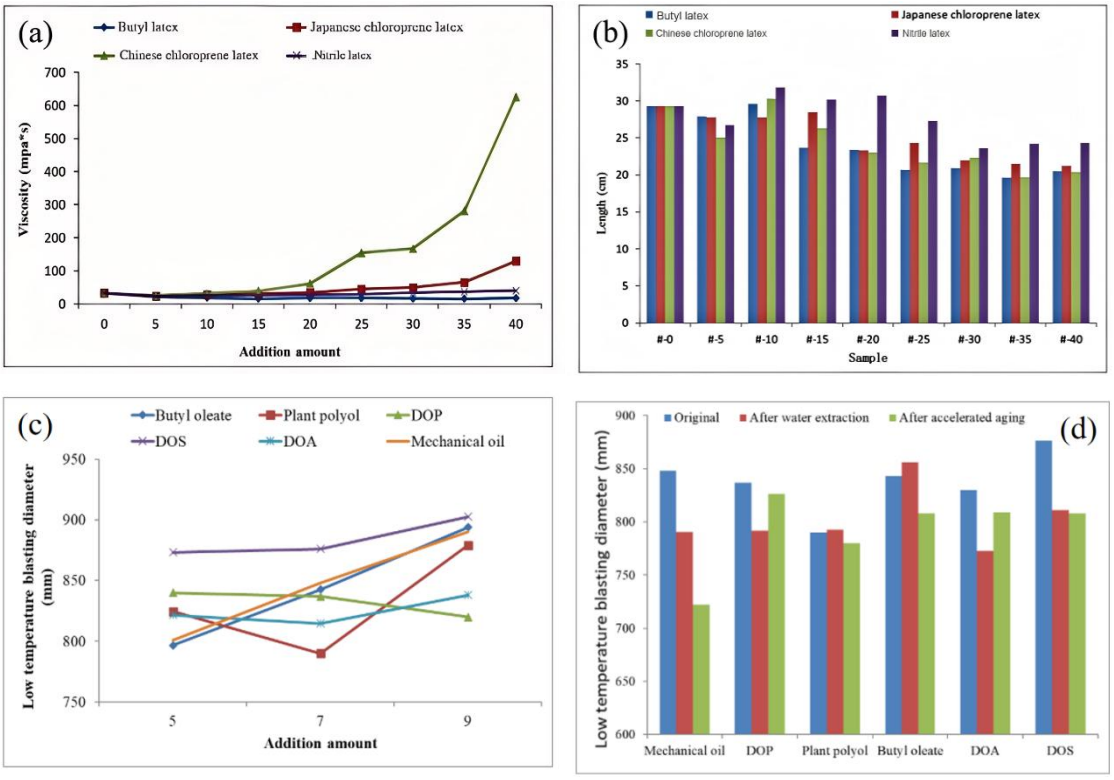
Table 2. Aeration test results based on coupling model.

Inflatable mode	Effective launch times	Drift number of times	Drift success rate	≥4h number of times	≥4h success rate
Algorithm software	611	479	78.40%	436	71.36%

Table 2 presents data from six stations (Changsha, Wuhan, Anqing, Yichang, Nanchang, and Ganzhou) situated along the middle and lower reaches of the Yangtze River in 2021. Using the coupling model, we calculated the aeration capacities of the inner and outer balloons and determined the success rate of the dual-mode balloon launches. The results demonstrate that the coupling model effectively controls the aeration of dual-mode balloon, enabling them to achieve the intended ascent and drift measurements.

3.1.2 Performance improvement of the double - layer balloon

The ascent phase of meteorological sounding typically lasts between 1.5 and 2 hours. However, during the ADD process, the inner balloon of the dual-mode balloon is exposed to low temperatures, intense ultraviolet radiation, and high ozone concentrations for several hours or even up to ten hours. To address these challenges, the ADDRS research team conducted formulation tests to enhance the inner balloon resistance to these environmental factors, with a particular emphasis on natural latex modification, cold resistance, and anti-aging systems.Considering that latex hot air aging performance improves air tightness and balloons are exposed to prolonged sun exposure and hydrogen loss, the incorporation of a specific latex compound was found to augment durability. Fig. 3a and 3b show that the addition of latex formulas had minimal impact on the latex viscosity and the balloon appearance while improving its tensile strength and thermal aging resistance. Fig. 3c and 3d demonstrate that butyl oleate exhibits the lowest reduction in low-temperature burst performance after water extraction and accelerated aging, making it the best-performing cold-resistant agent. Consequently, this agent was integrated into the formula to bolster cold resistance.For the anti-aging system, illustrated in Fig. 3e and 3f, nano zinc oxide, which can be diluted directly with water to replace traditional zinc oxide, was used. Additionally, we incorporated antioxidants to enhance the balloons' resistance against ultraviolet and ozone degradation. These formula improvements extend the inner balloon lifespan under harsh conditions of low temperature, intense UV radiation, and high ozone levels. This enhanced durability has been applied to the inner balloon, resulting in an extended service life and a high success rate during the drift phase (Zhu et al., 2021; Shen et al., 2020).



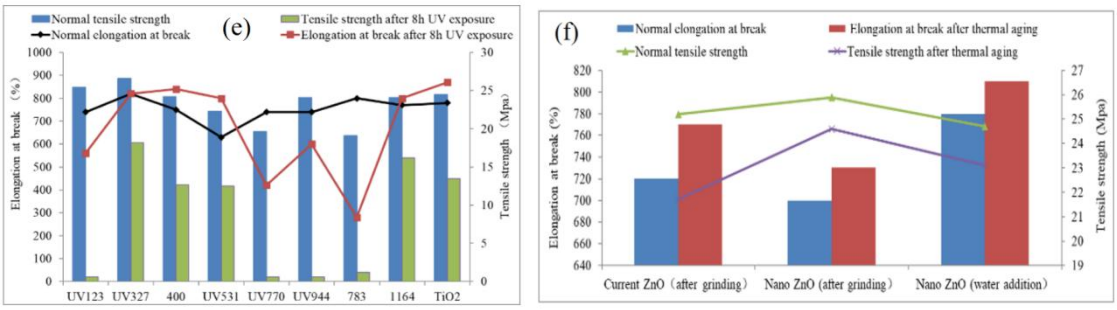


Figure 3. Modification test of natural latex in the inner sphere: (a) Four types of modified natural latex materials—Butyl latex, Japanese chloroprene latex, Chinese chloroprene latex, and Nitrile latex—were screened and added to natural latex using the homogenization method. (b) Physical properties of the modified natural latex pellet samples were evaluated for operational and thermal aging tensile testing. (c) Butyl oleate, Plant polyol,DdiOctyl Phthalate (DOP), DiOctyl Sebacate (DOS), DiOctyl Adipate (DOA), and mechanical oil were added to natural latex as cold resistance agents. Cold resistance system test:The blasting diameters of six types of cold-resistant samples were tested using low-temperature blasting instruments at -85°C. (d) Low-temperature blasting diameters were measured for six types of raw, water-pumped, and aged samples with seven parts of cold-resistant agents added. Anti-aging system test: (e) Comparison of tensile properties among nine anti-aging agents—UV327, UV400, UV531, UV1164, and TiO2 filler—with 0.2 parts of one-component anti-aging agent after eight hours of operational and ultraviolet aging. (f) Comparison of tensile properties after ozone aging between Nano ZnO and ZnO.

3.2. Payload technology

3.2.1 Specialized SoC module of meteorological-sounding

The ADDRS payload is similar to operational radiosondes and consists of three main components: positioning systems, PTU (Pressure, Temperature, and Humidity) sensors, and communication modules. It calculates and outputs satellite positioning information and performs real-time monitoring and transmission of meteorological data, including temperature, relative humidity, and pressure. Unlike operational radiosondes, ADDRS operates effectively across all three phases of the ADD process, requiring a minimum operational time of six hours. This extended operation necessitates a larger-capacity battery for the ADDRS radiosonde. Additionally, the radiosonde's weight affects the balloon's inflation volume, making it essential to reduce the radiosonde's weight where possible. Therefore, an integrated, lightweight, and low-power radiosonde is crucial, and the ADDRS research team developed a specialized SoC (System on Chip) module (named Equinox I) for CMA's GTH type of Beidou navigation radiosonde .

3.2.2 Highly integrated radiosonde

The Tianjin Huayuntianyi Special Meteorological Sounding Tech. Co., Ltd. HT-GTS(U)2-1 (GTH3) , which employs a specialized SoC module of meteorological sounding and utilizes a multi-layer board design and miniaturized components to reduce the size, weight, and power consumption. Table 3 demonstrates that the GTH3 radiosonde is significantly better than GTS1 radiosonde (Chinese operational radiosonde before 2025) in volume, weight, and transmission power, with advantages in operational duration and communication rate. The GTH3 participated in WMO UAII2022 (Upper-Air Instrument Intercomparison Campaign organized by the World Meteorological Organization (WMO) and co-organized by the Deutscher Wetterdienst (DWD) in 2022) with the results shown in Table 4. It is suitable for applications in ORUC(Operational and Research Use in Climatology), including aeronautic meteorology, near/ultra-short-term forecasting, global numerical weather prediction, and real-time monitoring (WMO IOM-143., 2024).

Table 3. Comparison of parameters among RS41, GTH3 and GTS1 radiosonde.

Radiosonde type	Positioning method	Volume (mm^3)	Weight (g)	Transmitting power (mW)	Working time (min)	Data Transmission Rate(bps)	Battery Weight (g)	Foam Packaging Weight (g)	Circuit boards Weight (g)
GTS1 radiosonde	Radar positioning	190×90×245	<400	400≤	>120	1200	<250	<70	<80
GTH3	Equinox I	155×65×60	<120(for one profile)	100≤	>240	Optional,2400,4800,9600	<40	<30	<50
		155×65×60	<170(for "ADD" three phase profile)	100≤	>640		<90	<30	<50
Vaisala RS41	u-blox G7020	155×60×46	109	60	>240	4800	76	/	/

Table 4. The evaluation results of GTH3 radiosonde temperature, pressure, relative humidity, wind and geopotential height in WMO Instruments and Observation Methods Report No. 143. page.150(Note: The data are in the form of $\Lambda_{c,L}{}^{\delta_{c,L}}_{\sigma(\delta)} \pm \epsilon_{c,L}$, where $\Lambda_{c,L}$ represents the individual measurement root mean square error, $\epsilon_{c,L}$ denotes the measurement uncertainty, $\delta_{c,L}$ is the measurement error, and $\sigma(\delta)$ indicates the measurement standard deviation. The planetary boundary layer (PBL) ranges from surface to 2 kilometers; the free troposphere (FT) ranges from 2 kilometers to the tropopause 12 kilometers are in the ; the upper troposphere/lower stratosphere (UTLS) ranges from 7 kilometers to 17 kilometers; the middle and upper stratosphere (MUS) is above 17 kilometers up to the bursting point of the sounding balloon.)

Time	Height	Atmospheric temperature [K]	Relative humidity [%RH]	Geopotential height [m]	Pressure [hPa]	Wind (horizontal)direction[°]	Wind (horizontal)speed [ms-¹]	Wind (horizontal)vector [ms-¹]
Day	PBL	$0.18^{-0.05}_{0.17}\pm0.03$	$7.00^{-5.43}_{4.41}\pm0.74$	X	X	X	X	X
	FT	$0.12^{+0.05}_{0.11}\pm0.04$	$8.75^{-3.50}_{8.02}\pm0.60$	$5.9^{+2.0}_{5.5}\pm1.8$	$0.4^{-0.0}_{0.4}\pm0.1$	$3.6^{-0.4}_{3.6}\pm0.2$	$0.2^{-0.0}_{0.2}\pm0.0$	$0.3^{+0.2}_{0.1}\pm0.0$
	UTLS	$0.09^{+0.01}_{0.08}\pm0.03$	$7.73^{-1.55}_{7.58}\pm0.40$	$13.2^{+10.0}_{8.6}\pm3.8$	$0.4^{-0.3}_{0.2}\pm0.1$	$2.5^{-0.2}_{2.5}\pm0.3$	$0.2^{-0.0}_{0.2}\pm0.0$	$0.3^{+0.2}_{0.2}\pm0.0$
	MUS	$0.27^{-0.22}_{0.16}\pm0.10$	$1.69^{+1.48}_{0.82}\pm0.46$	$29.5^{+23.4}_{17.9}\pm4.2$	$0.3^{-0.2}_{0.1}\pm0.0$	$6.1^{-0.4}_{6.1}\pm0.2$	$1.3^{-0.0}_{1.3}\pm0.0$	$1.5^{+0.3}_{1.5}\pm0.0$
Night	PBL	$0.38^{-0.18}_{0.34}\pm0.05$	$4.72^{+0.74}_{4.66}\pm0.15$	X	X	X	X	X
	FT	$0.15^{+0.02}_{0.15}\pm0.02$	$6.41^{+2.16}_{6.03}\pm0.11$	$5.8^{+0.4}_{5.8}\pm0.4$	$0.5^{+0.1}_{0.5}\pm0.2$	$2.6^{-0.2}_{2.6}\pm0.2$	$0.2^{-0.0}_{0.2}\pm0.0$	$0.2^{+0.2}_{0.1}\pm0.0$
	UTLS	$0.12^{+0.06}_{0.10}\pm0.05$	$6.82^{+3.70}_{5.74}\pm0.26$	$11.5^{+7.7}_{8.6}\pm3.4$	$0.3^{-0.1}_{0.2}\pm0.1$	$2.4^{-0.1}_{2.4}\pm0.1$	$0.2^{+0.0}_{0.2}\pm0.0$	$0.2^{+0.2}_{0.1}\pm0.0$
	MUS	$0.10^{-0.03}_{0.10}\pm0.02$	$1.71^{+1.54}_{0.74}\pm0.28$	$26.7^{+20.7}_{16.8}\pm4.2$	$0.1^{-0.1}_{0.1}\pm0.0$	$4.5^{-0.6}_{4.4}\pm0.2$	$0.2^{-0.0}_{0.2}\pm0.0$	$0.4^{+0.3}_{0.3}\pm0.0$

3.2.3 Drifting controller

The drifting controller can be considered part of the ADDRS payload. It connects to an inner balloon above and a parachute and radiosonde below. The controller fuses a wire with an instant high electric current, triggering the mechanical device to disconnect the parachute and the radiosonde. The controller serves two main functions during the drift phase:

1. Reduce the weight of the sounding equipment by releasing a pre-carried counterweight, in order to adjust the gravity or altitude of the inner balloon and its load during the drift phase.
2. Separate the inner balloon from the other sounding equipment (parachute and radiosonde). Moreover, the drifting controller can also initiate the fuse based on predetermined control rules, such as altitude limits (≤18 km), specified time, the latitude and longitude of a designated area, or upon receiving commands from the ground. This action can be taken before the drifting balloon is about to enter the specified area or approach the maximum drift height. As a result, it will effectively end the drift phase, separating the parachute and radiosonde from the balloon.

3.3. Receiving radiosonde data and sending control instructions technology

The ADDRS ground data-receiver utilizes a high-gain, low-power, ultra-compact omnidirectional antenna, along with super-heterodyne architecture and multiple communication protocol algorithms, including time division multiple access, frequency division multiple access, and code division multiple access (Gong et al., 2021). It supports various frequency modulation modes and achieves a receiving sensitivity of better than -120 dBm (at 2400 bps), effectively addressing self-interference issues in multi-channel radiosonde data reception. Additionally, the system incorporates narrow-band wireless communication technology to improve low-elevation reception when the radiosonde drops below the receiving antenna's height, facilitating broad-area coverage with a visual range radius for upper-air coverage of at least 200 km. The receiver can adapt to diverse application scenarios, such as fixed stations, vehicles, and ships. With an average data reception rate of 99.7%, the ground receiver at the Anqing station has demonstrated an impressive maximum reception distance of up to 487 km.

Unlike the one-way (downlink) communication mode used in operational sounding systems, the ADDRS control command transmitter can send ground instructions to the drifting controller, with a linear communication range extending beyond 300 km. This capability allows for precise control over the drifting controller to execute actions such as releasing counterweights or separating the balloon from the parachute and radiosonde, enabling the radiosonde to conduct drift phase measurements within the target area (Liu et al., 2021). During field tests, over ten balloon discharge control commands were successfully transmitted, with the farthest reaching 403 km.

3.4. "ADD" measurement technology

The details of the ADD measurement method are outlined by (Cao et al., 2019). The ascent phase measurement technique adheres to the guidelines outlined in the Guide to Operational Upper-Air Meteorological Observation. The primary research focus of the ADDRS is on the measurement techniques for the drift and descent phases.

3.4.1 Temperature measurement method in the flat drift phase

During the drift phase of ADDRS, the inner sphere of the dual-mode balloon moves with the horizontal airflow in the stratosphere. The radiosonde's vertical movement, with the surrounding atmosphere, is minimal and can be approximately considered as drifting with the horizontal wind. The effect of radiation on the temperature sensor during this phase is significantly greater than during the ascent and descent phases, leading to considerable measurement errors that are challenging to correct using general quality control algorithms. For instance, Vaisala RS41 radiosonde software often flags such data as invalid in operational radiosonde observations.

Given the unique conditions of stratospheric air temperature measurement, the ADDRS research team employs a multi-physical field, fluid-structure coupled computational fluid dynamics (CFD) approach to model the behavior of the temperature sensor in high-altitude, low-wind-speed environments. This model calculates the flow and the temperature field, accounting for radiation effects based on sun elevation, ventilation, sensor size, and surface reflectivity. To ensure broad applicability, neural networks, and other mathematical methods are used to fit the extensive simulation data, yielding practical error-correction equations (Yang et al., 2014).

Considering that there may be discrepancies between CFD simulations and real environmental conditions, the ADDRS research team uses instruments such as low-pressure wind tunnels and solar simulators to create an experimental platform. This setup simulates ventilation, air density, and solar radiation conditions during the drift phase, allowing for the measurement of temperature errors due to solar radiation. These measurements verify and refine the simulation-based error correction equations (Yang et al., 2022).

3.4.2 Vertical wind data extracted by parachute landing

Currently, due to the pendulum effect, vertical wind measurements cannot be performed in balloon-borne soundings. The parachute-drop wind measurement model established by the WMO and NCAR does not address vertical wind measurement directly(Wang et al., 2015), instead assuming a zero vertical wind speed. This model assumes that the parachute-drop system is influenced only by gravity and vertical resistance, omitting other factors like buoyancy, additional forces, and parachute rotation during descent. This limitation prevents the analysis of vertical wind and also affects the accuracy of horizontal wind field calculations (Jensen et al., 2010; Ingleby et al., 2022).

Therefore, the ADDRS research team developed a more comprehensive vertical wind measurement model by considering all relevant forces acting on the parachute descent system (Guo et al., 2018). Comparative tests led to the selection of conical parachutes to minimize swing effects on measurements, with the parachute area tailored to match the radiosonde weight. As a result, ADDRS achieves a stable descent speed of approximately 6 m/s ± 1 m/s, a swing angle below 5°, and a vertical wind measurement uncertainty of less than 1 m/s. These findings demonstrate that the model is effective for calculating vertical wind.

4. Field experiments and data quality verification

4.1. Field experiment in the middle and lower reaches of the Yangtze River Region

From 2019 to 2021, ADDRS conducted field tests and application research across a wide area in the middle and lower reaches of the Yangtze River in China. The research focused on measurement data processing

methods, quality control algorithms, and application technologies across diverse scenarios. The ADDRS network spans six stations: Anqing, Wuhan, Yichang, Nanchang, Changsha, and Ganzhou, located in Anhui, Hubei, Jiangxi, and Hunan provinces. A total of 14 ground radiosonde data receivers were strategically positioned around these six stations, spaced approximately 150 km apart. The test covered an area of 600,000 square kilometers, as shown in Fig. 4, and show a trajectory for ADDRS at the Anqing station at 12:00 UTC on 11 July 2021.

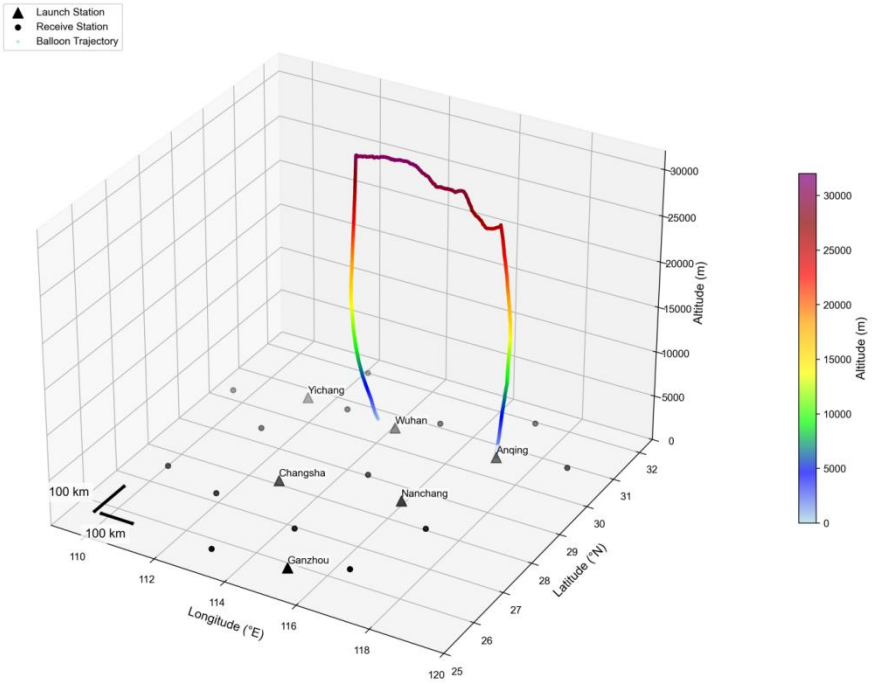


Figure 4. The network distribution of ADDRS and an example of measurement: the trajectory for ADDRS at the Anqing station at 12:00 UTC on 11 July 2021. The black triangles represent balloon launch stations of ADDRS , while the black dots represent receive radiosonde data stations of ADDRS.

During the 13-month experimental period, 3,177 ADDRS launches were conducted, with 3,012 classified as effective launches, of which 2,369 achieved successful drifting. Among these, 2,136 launches resulted in drifting for more than 4 hours. The overall drifting success rate was 78.65%, with a 4-hour drifting success rate of 70.91% (Fig. 5).

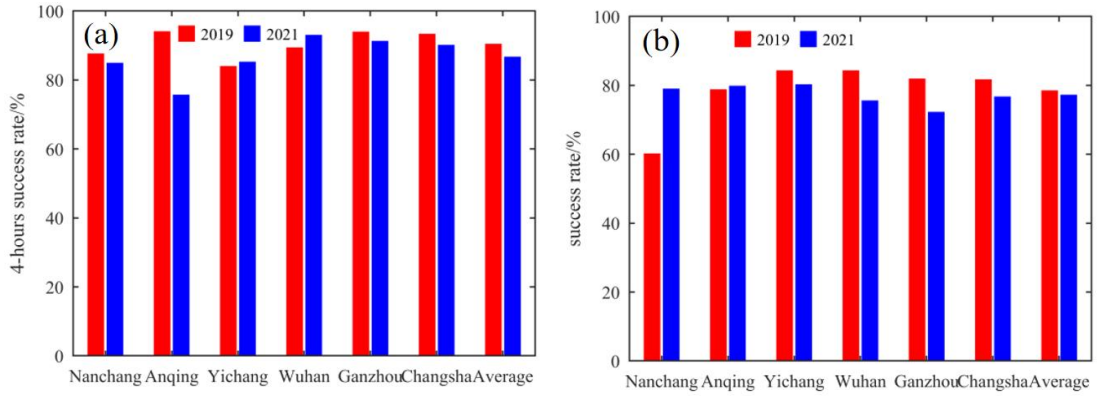


Figure 5. The field experiment in the middle and lower reaches of the Yangtze River Region (2019-2021): (a) Drifting success rate; (b) 4-hour drifting success rate.

From March to September 2021, 2,427 “ADD” radiosonde launches were conducted, with 2,281 classified as effective launches,of which 1,772 achieved successful drifting. Among these, 1587 launches resulted in drifting for more than 4 hours. The overall drifting success rate was 77.68%, with a 4-hour drifting success rate of 69.57%. The 1,772 successful drifts were analyzed (Fig. 6), and 937 were successful during the daytime, accounting for 52.88%. The successful nighttime drifting was 835 times, accounting for 47.12%, and the effect of daytime was better than nighttime. The drift heights ranging from < 75hPa (<18km) to 15hPa-10hPa (28km-32km) were statistically analyzed. The proportion of outer ball explosion heights within 15hPa-10hPa (28km-32km) was the largest (42.89%). And the proportion of 20hPa-15hPa (26km-28km) is 40.35%, the proportion of 30hPa-20hPa (24km-26km) is 8.97%, and the total proportion of beyond 30hPa is 92.21%. Therefore, the drift height should basically meet the 30hPa requirement of GBON (WMO, 2020).

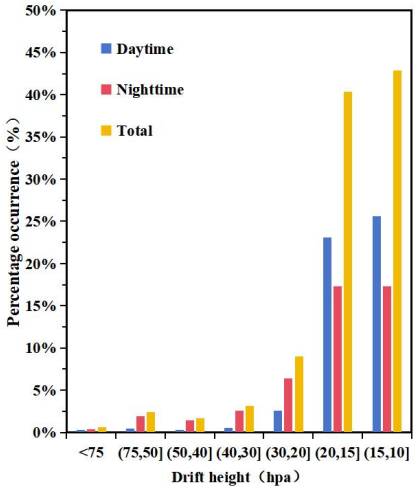


Figure 6. The sounding-forecasting interactive network experiment (2021): (a) drifting height; (b) descent height.

Due to the limited availability of high frequency, continuous measurement data for the stratospheric atmosphere, experiments were conducted in the middle and lower reaches of the Yangtze River to obtain direct measurement data with high spatial and temporal density (Zhang et al., 2021). The simulated and observed trajectories are represented by red and black, respectively (Fig. 7). A color gradient based on pressure altitude is used to indicate the variation of trajectory height along the path.

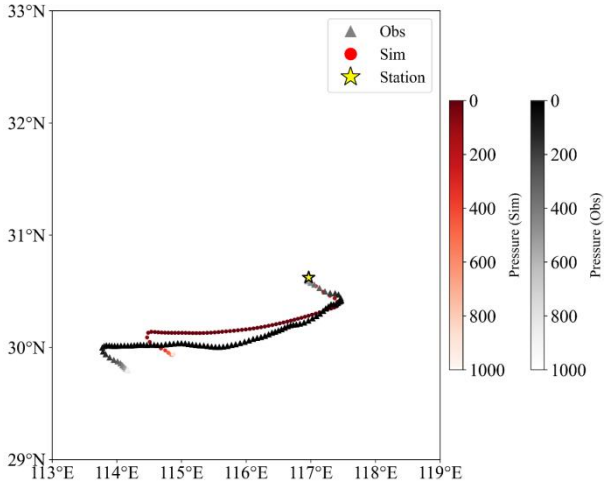


Figure 7. Observation (black triangles) and simulation (red dots) trajectory diagram. The yellow pentagrams represent radiosonde observations stations, and the colour of the dots represent the corresponding pressure heights.

The colour range from light to dark, indicating the process of the trajectory rising from low altitude (high pressure) to high altitude (low pressure).

The balloons drifting of ADDRS radiosondes data in stratosphere have been very useful for verification FY-3D satellite temperature and humidity profiles (Zhou et al., 2023; Zhou et al., 2024) .And application in observing certain features of gravity waves in the lower stratosphere (He et al., 2024; Yang et al., 2021) and feature extraction and analysis of atmospheric turbulence (Yang et al., 2023).

4.2 Data quality evaluation

Aiming at the characteristics of high-resolution ADDRS data for quantitative application, the ADDRS research team carefully evaluated ADDRS data using 31 data quality control methods based on the guidelines for operational upper-air meteorological observation (Wang, D et al. 2020). For the data quality of the ascent phase of the ADD radiosonde, refer to the results in Table 4. Additionally, the fifth generation of ECMWF (ERA5) global reanalysis (Hersbach et al., 2020) was used to evaluate the quality of four upper-air radiosonde observations stations' ADDRS data in Guangdong in August 2022in (Zhang, C.Z et al., 2025), and Table 5 shows the results of field experiment in the middle and lower reaches of the Yangtze River Region (2019-2021). Compared with the data in the ascent phase and the descent phase, the results for temperature, u-wind, v-wind, and the standard deviation of geopotential height show good consistency, relative humidity shows weaker uniformity. The conclusion is basically consistent with the results of Table 4 in the section 3.2.2.

Table 5. Comparative analysis of after-quality control of ADDRS radiosonde data and ERA5.

			U (m/s)		V (m/s)		T (K)		RH (% RH)	
			bias	std	bias	std	bias	std	bias	std
Ascent	Day	Above tropopause	0.03	1.73	0.11	1.91	−0.4	1.04	/	/
		Below tropopause	0.13	1.41	0.08	1.47	0.04	0.69	1.32	8.57
	Night	Above tropopause	−0.02	1.72	−0.01	1.87	0.01	1.02	/	/
		Below tropopause	0.13	1.4	0.02	1.46	0.08	0.66	1.62	8.32
Drift		above tropopause	/	3.32	/	3.22	/	3.09	/	/
Descent	Day	Above tropopause	0.16	1.74	−0.02	1.9	0.9	1.14	/	/
		Below tropopause	0.14	1.65	0.01	1.7	0.42	0.75	−1.7	10.12
	Night	Above tropopause	0.16	1.73	0.03	1.84	0.21	1.06	/	/
		Below tropopause	0.15	1.67	0.05	1.67	0.04	0.73	0.5	10.47

5. Application of ADDRS in numerical forecasting techniques

5.1 The applications in weather analysis

Through long-term testing, the ADDRS have the potential for capture key information in convective system monitoring. From July 8 to 9, 2021, a strong convective weather event with a long duration and a large impact area occurred in the middle and lower reaches of the Yangtze River in China. Convection developed and moved to northern Jiangxi, northern Zhejiang, southern Anhui, and southern Jiangsu overnight on July 8 (Fig.8). The drifting trajectories of ADDRS radiosondes were from west to east, which aligned with the movement and

development direction of severe convection. The descent phase radiosondes of ADDRS provides effective monitoring and significant insights in track the occurrence of the convective system and the changes in the ambient field.

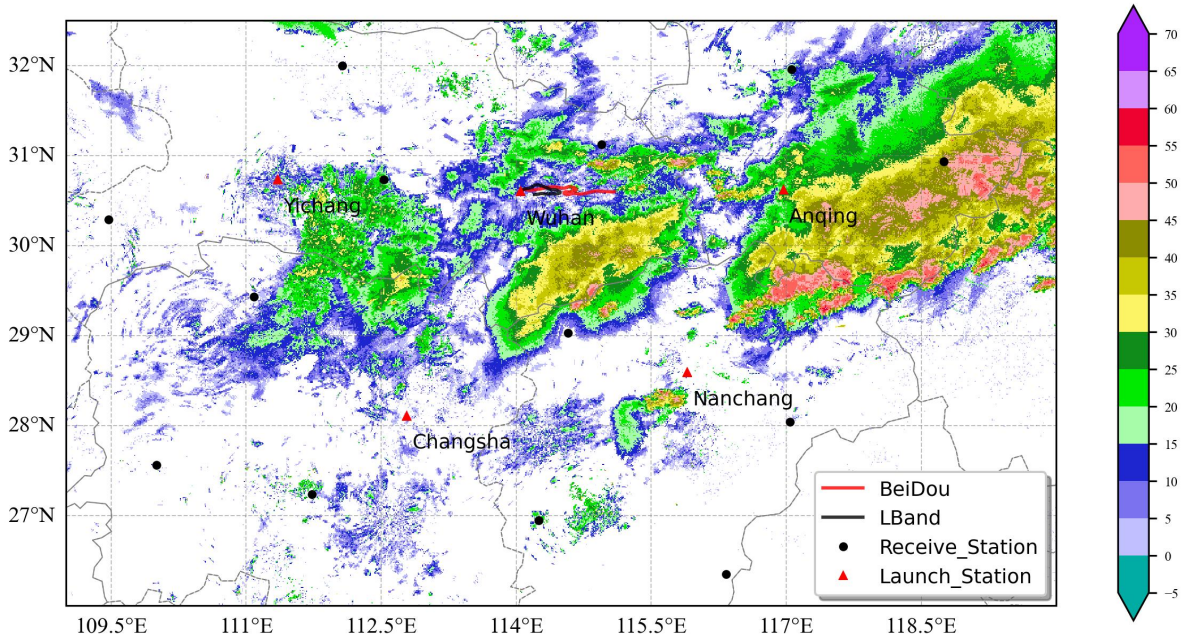


Figure.8 The trajectory for Beidou radiosonde and LBand(GTS1) radiosonde at the Wuhan station and radar reflectivity image at 12:00 UTC on 11 July 2021.

Fig.8 presents the trajectory data for both the ADDRS(Beidou) radiosonde and the GTS1(LBand radiosonde), which were recorded at the Wuhan meteorological station. At 19:15 on the night of the 8th, Wuhan was located on the west side of the main body of the convection, and the ADDRS radiosonde was launched from the Wuhan station. Subsequently, at 20:00, the GTS1 radiosonde was also deployed from the same location. The trend of the ADDRS radiosonde curve in the ascent phase (Fig. 9b) mirrored the trend observed for the GTS1 radiosonde (Fig. 9a). It was evident from the radiosondes in the ascent phase that the CAPE values of the ADDRS radiosonde and GTS1 radiosondes differed with the development of convection. The CAPE value of the GTS1 at 20:00 was 1729.39 J/kg, exceeding the 1498.16 J/kg detected by ADDRS radiosonde at 19:15. Influenced by an upper-level westerly jet, the ADDRS sounding balloon drifted eastward toward the Wuhan. At 21:30, ADDRS conducted descent phase measurements (Fig. 9c). As shown in the layer curve, the CAPE value at 21:30 decreased significantly compared with that at 20:00, dropping to 646.0J/kg, which was lower than the energy recorded at the Wuhan station. There is still a westerly jet stream with wind speed greater than 20m/s beyond the upper-air of 500hPa level. The east of Wuhan proximity to the main body of convection, the reduction in energy suggests intensive of upward motion, leading to the reduction of effective potential energy and further develop of convective. Notably, the GTS1 radiosonde, launched from Wuhan, ceased data collection after the ascent phase, thus missing this crucial change. The descent phase of ADDRS demonstrates robust monitoring capabilities and holds significant implications, as it can timely captures environmental conditions favorable for convection onset and development, including wind patterns, effective potential energy,

and humidity at downstream locations.. These findings enable researchers to analyze changes in the upper-air field and the occurrence of catastrophic weather convective systems.

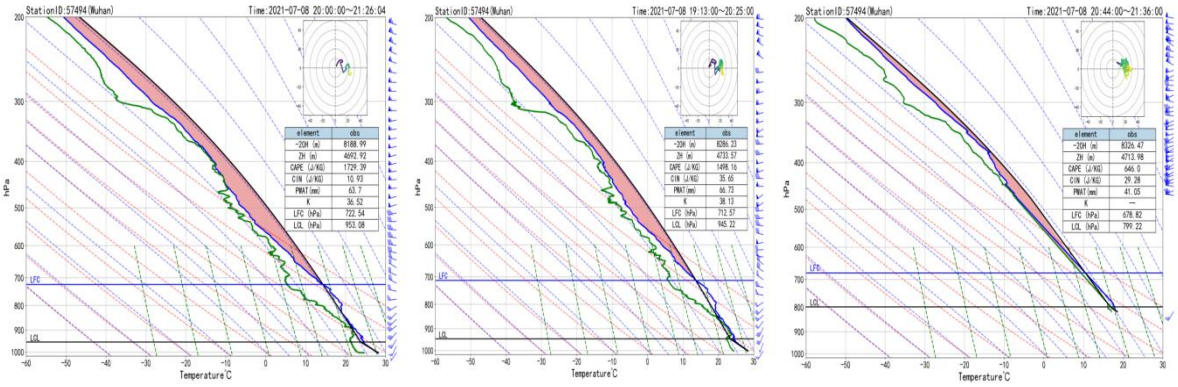


Figure 9. Comparison of ADDRS and GTS1 radiosonde T-logP at the Wuhan station: (a) GTS1 radiosonde; (b) ascent phase of ADDRS radiosonde; (c) descent phase of ADDRS radiosonde.

5.2 Applications in numerical weather prediction (NWP)

Compared with GTS1 radiosondes, the ADDRS radiosondes of ascent and descent phase measurement data for numerical weather prediction (NWP), achieving a similar role to intensive sounding and providing more continuous, direct stratospheric measurement data (Zhang, X et al., 2025; Zhang, X.P et al. 2023). The Numerical Department of the China Meteorological Administration developed the key technology for ADDRS assimilation in the CMA-MESO 3DVar (three-dimensional variational mesoscale) (Zhuang et al. 2019) and CMA-GFS 4DVar systems (four-dimensional Variational Global Forecast System) (Wang, R. W et al., 2021). To avoid the tangent linear and adjoint models, the four-dimensional ensemble forecast error is introduced into the CMA global data assimilation system, and the Hybrid-4DEnVar assimilation scheme is developed. The batch cycling forecast experiments and typhoon forecast experiments are conducted and compared with the 4DVar scheme (Gong et al., 2019; Wang, F et al., 2024). Specifically, this includes observation operators that consider drift positions and vertical sparring methods, such as selecting the nearest radiosonde data from the model layer for assimilation. We employed the CMA-MESO system to conduct a measurement data assimilation in the ADDRS descent phase across six test stations in the middle and lower reaches of the Yangtze River from July 1 to July 31, 2021. We set up the control test (CTL) as in the CMA-MESO system, and the observed data included traditional sounding data, ground reports, aircraft reports, cloud-guided wind, radar radial wind, GNSS occultation refractive index, and ground-based GNSS retrieval of the atmospheric whole-layer precipitation water. ADDRS data assimilation was added to the control CTL in the Down test.

The impact of the ADDRS descent phase measurement data on the precipitation forecast at CMA-MESO at 03, 06, 09, 15, 18, and 21 UTC (termed the warm start times) was evaluated. Compared to the TS (Threat Score), the ETS (Equitable Threat Score) imposes stricter penalty for false alarms and missed reports, making the scoring more equitable. The results of the one-month batch test indicate that assimilating ADDRS descent phase data improves precipitation forecasting skills, especially for heavy precipitation above a certain magnitude. Fig. 10a and Fig. 10b illustrate the improvement rates in accumulated precipitation forecasting skills for the 0-12 hour and 12-24 hour periods from the warm start time. Positive values indicate that the precipitation forecasting skills of the Down test are improved compared with those of the CTL test, while negative values indicate a

decrease in forecasting skills for the Down test. The ETS scores for precipitation forecasts in the 0-12 hour range at thresholds of 0.1 mm, 1 mm, and 50 mm increased slightly, averaging about 0.04% (Fig. 10a). Due to the timeliness required for forecasting, the 12-24 hour precipitation forecast is of particular interest to forecasters. As illustrated in Fig. 10b, the Down test demonstrated enhanced ETS scores for precipitation forecasts across all levels within the 12-24 hour range, with an average increase of 0.7% at the 50 mm threshold and a notable 2.2% improvement specifically at this level .

In addition, we utilized CMA-MESO V5.1 to conduct Observing System Simulation Experiments (OSSE) under the ADDRS network nationwide. The results indicate that once the ADDRS network observation is implemented, the national precipitation forecast skills of the CMA-MESO fast cycle assimilation forecast system at warm startup time can improve by 2%-5%. The potential operational applications of ADDRS high-resolution data were quantitatively evaluated using a numerical model (Wang, R. W et al., 2023). After the application of ADDRS data in CMA-GFS 4DVar assimilation, the temperature analysis error at 06:00 and 18:00 was reduced by more than 2% and the average prediction skill of the CMA-MESO accumulated precipitation results for the 12-36 hour period improved by 1% (Wang, J. C. et al., 2024).

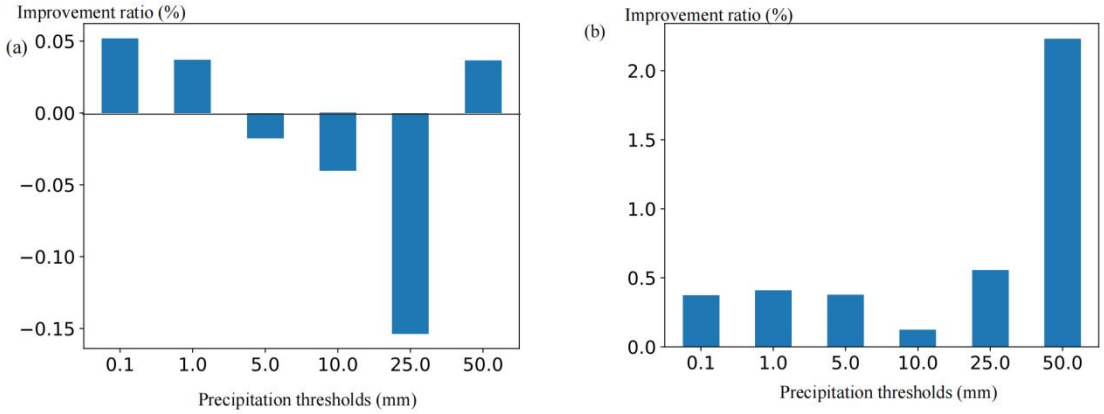


Figure 10. Improvement rates of cumulative precipitation thresholds (mm) predictions for 0-12 hours (a) and 12-24 hours (b) in the Down test compared to the control test.

5.3 Applications in targeted observations

Targeted observation have sometimes been one of frontier field in atmospheric science research. They represent an important method to address the shortcomings of operational observation systems in monitoring extreme weather events. Furthermore, they significantly enhance the initial field quality and forecast accuracy of numerical models, which is crucial for predicting extreme weather disasters (Majumdar., 2016). With its capacity for “ADD” measurement, the ADDRS has the potential to conduct targeted observations in uninhabited areas, rarely observed regions, and during specific extreme weather events. However, since the ADDRS lacks a power system, accurate trajectory prediction is essential for utilizing the descent phase for vertical measurements in these locations. This requires careful consideration of appropriate drift height, launch time, and launch location, allowing the ADDRS sounding to be carried to the target observation area by the ambient wind field.

In this context, a trajectory prediction and selection method based on high-resolution numerical weather prediction technology has been proposed for ADDRS (Wang, J. C et al., 2021). Additionally, Majumdar (2016)

highlights that advancements in numerical weather prediction (NWP) systems—such as improved data assimilation techniques and enhanced model resolution—have reduced the marginal contributions of individual observing systems. Furthermore, the evaluation of targeted observations is constrained by factors including flow-dependent conditions, limited sample sizes, and inconsistencies in verification metrics. Therefore, cost-effective strategies for targeted observations necessitate exploration through multi-agency coordinated observing system experiments, such as FSO studies (Magnusson.et al., 2025).

5.3.1 Trajectory prediction method and software system

The issues of low temporal resolution and prediction accuracy associated with the linear extrapolation method used in balloon trajectory prediction (Brown et al., 2024). The balloon trajectory equation is directly embedded into a high-resolution numerical weather model system that utilizes a model atmospheric environment with high temporal resolution (1-10 seconds) and high spatial resolution (1-3 km). This approach enables precise simulation of vertical velocity during the ADDRS descent phase (Fig. 11a), significantly enhancing the accuracy of ADDRS trajectory prediction and the simulation of descent velocity. The average prediction error for a 6-hour trajectory is less than 40 km (Fig. 11b).

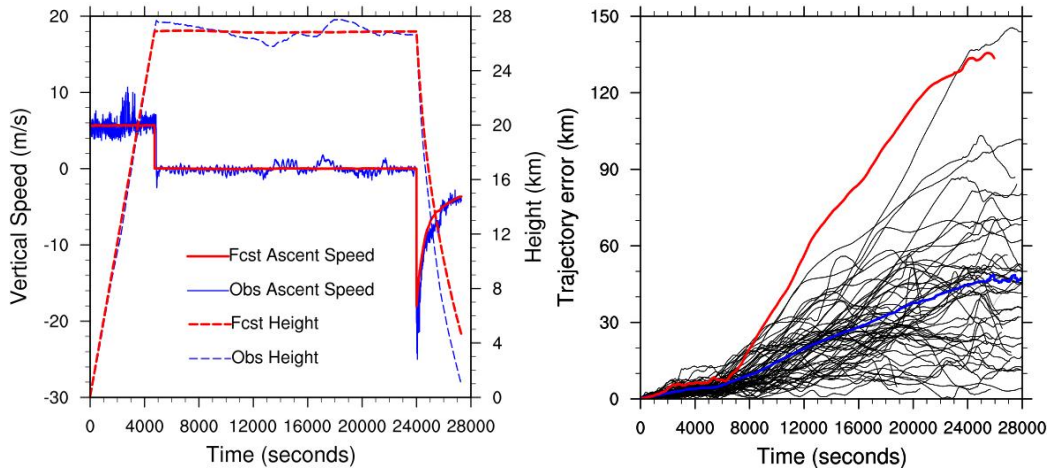


Figure 11. (a) Comparison of simulated (red line) and observed (blue line) vertical speeds of ADDRS radiosonde data during the descent phase at the Anqing station at 11:17 on June 20, 2018; (b) Deviations of 63 pairs of simulated ADDRS trajectories versus observed trajectories (black line), with the average deviation indicated by the blue line and the largest forecast deviation shown by the red line.

5.3.2 Trajectory selection method based on the collection idea

To observe the ADDRS in the target observation area, we proposed a method of elevation selection based on ensemble forecasting, considering the characteristics of the atmospheric wind field as it varies with altitude. The main idea of this method is to predict the trajectories of all ADDRS stations at different drifting heights and select the heights closest to the target observation area. The details are as follows:

1. Identify the positions and launch time: Given the positions $Sm(x_m,y_m,z_m)$ of M ADDRS launch stations and the launch time t_r .
2. Select safe drift heights: Choose N safe drift heights h_1, h_2... .h_n, that comply with civil aviation safety regulations as flat drift heights.

3. Trajectory prediction: Utilize the trajectory prediction system to predict the ADDRS trajectories under the above conditions within 12 hours, resulting in Tnm(x,y,z,t) for N trajectories at each of the M launch stations.
4. Calculate closest trajectory: From the M×N trajectories obtained in step 3, calculate the trajectory closest to the target observation point. When the distance is less than the predetermined standard distance L_C that can meet the requirements, the releasing ADDRS station and the drifting height H_s are selected, and the time nearest to the target area is taken as the descent time t_s. If no suitable drift height meets the conditions, the trajectory selection fails.
5. Implement target observation: Input the information regarding the ADDRS balloon launch station, drift height, and descent time determined in step 4 into the ADDRS operation command system to execute the target observation.

5.3.3 Targeted observations experiment of Typhoon

The ADDRS research team proposed a 'full chain' implementation for target observation using ADDRS (Fig. 12). This implementation plan, designed to provide technical support for ADDRS applications in disaster weather monitoring, forecasting, and mechanism research, encompasses three primary stages. Initially, the requirements for target observation are established. These requirements fall into two categories: one focusing on specific disaster weather events and the other on sensitive areas to improve future numerical prediction skills. The target observation area is then determined based on the type of demand. For the first category, the specific location of anticipated disaster weather is identified through numerical prediction results. For the second category, the target observation location is determined using CMA-GFS singular vector technology.

Subsequently, the trajectory selection system is invoked to ascertain the ADDRS discharge radiosonde observations station, drift height, discharge time, and other relevant information. This information is then transmitted to the operation command system of ADDRS to guide the stations in implementing ADDRS measurements. Ultimately, the ADDRS target observation data is distributed to users for application and evaluation.

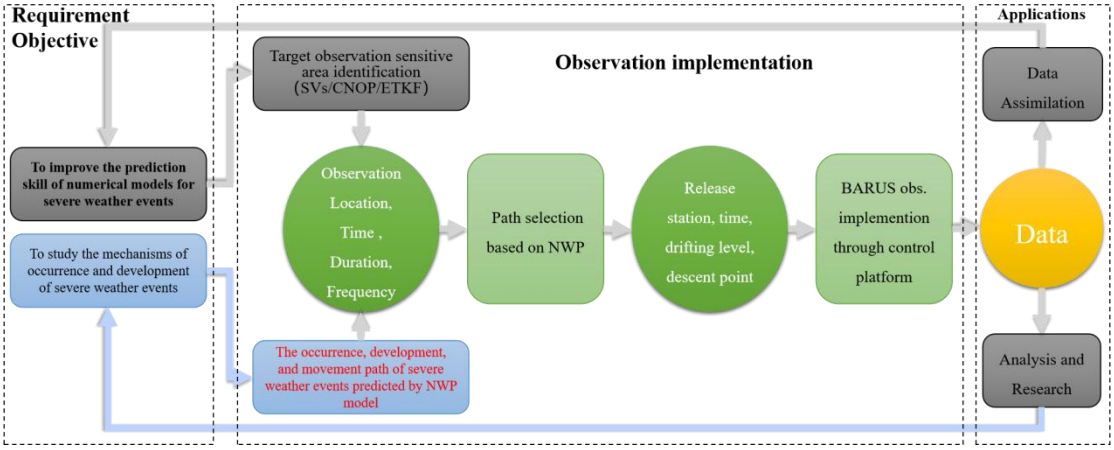


Figure 12. Technical route for targeted observations of typhoons and other severe weather using ADDRS and CMA-MESO models.

According to the implementation plan for ADDRS target observation (Zhang et al., 2021; Liu, L. H et al., 2022), we made a preliminary attempt to conduct a target observation experiment on Typhoon 2309 'SAOLA'

(Lau et al., 2024) formed at 00 UTC on August 28, 2023. By 00 UTC on September 1, it was expected that 'SAOLA' would land near Guangdong on September 2. Therefore, the demand for vertical profile data of the internal interface of Typhoon 'SAOLA' became imperative.Using the typhoon trajectory predicted by CMA-GFS, we pinpointed the typhoon's position for 12:00 PM on September 2 post-landfall. The ADDRS trajectory selection system was then engaged to ascertain the balloon launch station and drift height that could reach or come closest to the typhoon area, ranging from the minimum navigation safety height of 21 km to 29 km. We set ten different drift levels at 1 km intervals, with trajectory predictions and simulations conducted from four radiosonde observations stations in Guangdong. Yangjiang radiosonde observations station in Guangdong was ultimately chosen for the launch, scheduled for 06:00 on September 2, 2023, with a drift level of 25 km.

We calculated the required air capacity for the dual-mode balloon, and the 'ADD' subsystem was prepared to be deployed by radiosonde observations station personnel. When the radiosonde reached the core area of 'SAOLA,' the radiosonde dispatched commands to the 'SAOLA' controller via control command transmission equipment, successfully observing the descent section 80 km from the center of Typhoon 'SAOLA.' The obtained ADDRS data was subsequently assimilated into the CMA_MESO 3DVar system. Late test results indicated that after assimilating the data from the ADDRS descent phase, the forecast error for the typhoon trajectory reported since 06:00 on September 2, 2023, was significantly reduced. Specifically, the typhoon trajectory error at 02:18 was reduced from 62.7 km to 35 km in the control test ,marking an improvement of 44.18%. Additionally, precipitation forecasting techniques exhibited significant improvements: from 0.25 to 0.30 in the 10 mm scale, from 0.30 to 0.55 in the 25 mm scale, and from 0.45 to 0.70 in the 50 mm scale. These results effectively demonstrate the potential of ADDRS in target observation and numerical assimilation applications (Fig. 13). It is worth noting that the initial use of ADDRS for target observation served as a foundational attempt, paving the way for future ADDRS operations and maximizing its utility (Wen., et al., 2024).

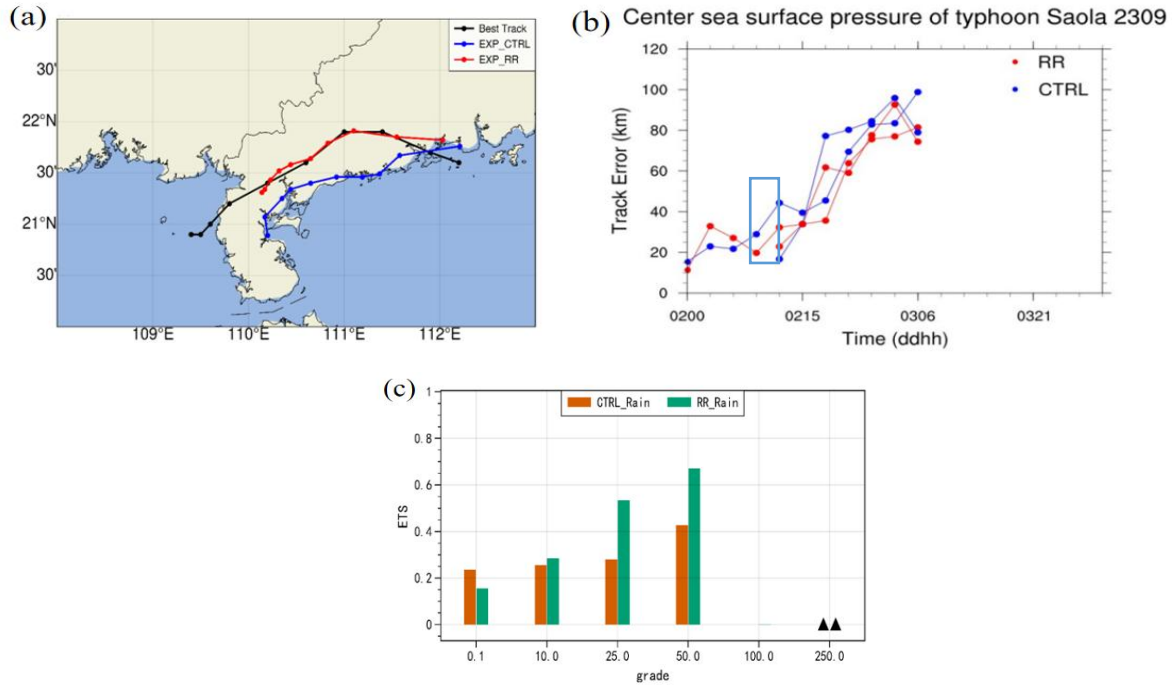


Figure 13. 2023-09-02 UTC 00-12h: (a) Control test (blue), ADDRS data assimilation impact test (red), and optimal trajectory of Typhoon 'Saola' (black); (b) Comparison of sea level pressure at the central point of Typhoon 'Saola'

between the control test (blue) and the ADDRS data assimilation impact test (red); (c) ETS scores for 0-24 hours of precipitation forecast from control trials (orange) and ADDRS data assimilation impact trials (green).

6. Summary

Distinct from operational balloon soundings, ADDRS created a new model, which is achieved a three-phase sounding at one launch by effectively incorporating ascent profile sounding, stratospheric drift and descent soundings. As well as ADDRS represents a next-generation approach to acquiring upper-air data, surpassing the 20th century operational method. We developed a multi-station real-time reception system utilizing 'Internet cloud + Instruments terminal' technology. Additionally, uplink commands can be sent from the ground to facilitate descent measurements in designated areas and targeted observations in weather-sensitive regions. Following over five years of extensive research and numerous field tests, the instruments, software, and operational guidelines of the system have achieved a refined level of maturity. Starting January 1, 2024, ADDRS already undergo operational experiments at four radiosonde observations stations in Guangdong, China. Since July 2024, a planned operational trial at 127 CMA radiosonde observations stations aims to achieve full operational capability across all CMA radiosonde observations stations by 2026. ADDRS is a situational profiling technique that offers cost-effective upper-air measurements, making it suitable for widespread application in operational soundings. However, challenges remain, such as improving the drift success rate, enhancing relevant technologies, and fully leveraging the potential of continuous measurement data during the drift phase. With the constant development of ADDRS and the continuous deepening of the measurement data, ADDRS will become a development direction for future operational upper-air observation applications and scientific research.

Data availability: Due to its proprietary nature <or ethical concerns>, supporting data cannot be made openly available. Further information about the data and conditions for access are available at the [National Earth System Science Data Center] at[https://www.geodata.cn/collect/site/#/].

Xiaozhong Cao1, Qiyun Guo2, Haowen Luo2, Rongkang Yang2, Peng Zhang2, Guo Jianping3, Jincheng Wang4, Die Xiao5, Jianping Du6, Zhongliang Sun7, Shijun Liu8, Sijie Chen9, Anfan Huang2

Author contributions. XC, QG and HL designed the experiments and wrote the paper; JW, DX, JD, ZS, SL carried out the experiments; RY, JW analyzed the experimental results. PZ, GJ, SC, AH revised the paper and participated in the discussion.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Disclaimer. Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors.

Financial support. This research has been supported by the National Natural Science Foundation of China (grant no. U2442214) ; the National Key Research and Development Program (grant no. 2018YFC1506200) ;the Innovation Team of the China Meteorological Administration(grant no. CMA2023QN11)..

REFERENCES

Anand, D., Kumar, B. S., and Ojha, D.: TIFR Zero-Pressure balloon program crosses a milestone, Current Science, 2021, 120, 1672-1678, doi:https://doi.org/10.18520/cs/v120/i11/1672-1678.

Bauer, P., Thorpe, A., Brunet, G.: The quiet revolution of numerical weather prediction, Nature, 2015, 525, 47–55, doi:https://doi.org/10.1038/nature14956.

Bormann, N., Lawrence, H., Farnan, J.: Global observing system experiments in the ECMWF assimilation system, ECMWF Technical Memorandum 2019, 839, 24 pp., doi:https://doi.org/10.21957/sr184iyz.

Brown, D., Linz, M. & Leidich, J. Seasonal and geographic viability of high altitude balloon navigation. Sci Rep 14, 21861 (2024). doi:https://doi.org/10.1038/s41598-024-71445-9.

Cohn, S. A., and Coauthors, 2013: Driftsondes: Providing In Situ Long-Duration Dropsonde Observations over Remote Regions. Bull. Amer. Meteor. Soc., 94, 1661–1674, doi:https://doi.org/10.1175/BAMS-D-12-00075.1.

Cao, X. Z., Xia, Y. C., Luo, H. W., Liu, L. H., Liu, Y. F., Liu, Z. Y., Li, X., Guo, R., and Guo, Q. Y.: Technical development and prospect of meteorological sounding measurement, J. Adv. Meteorol. Sci. Technol, 12, 27-36, 2022, doi:https://doi.org/10.3969/j.issn.2095-1973.2022.05.005.(in Chinese)

Cao, X. Z., Guo, Q. Y., Yang, R. K.: Research of rising and falling twice sounding based on long-time interval of flat-floating, Chinese Journal of Scientific Instrument, 2019,40(2): 198-204. http://yqyb.etmchina.com/yqyb/article/abstract/20190223?st=search. (in Chinese)

DuBois, J. L., Multhauf, R. P., and Ziegler, C. A.: Invention and Development of the Radiosonde with a Catalog of Upper-Atmospheric Telemetering Probes in the National Museum of American History, Smithsonian Institution, Smithsonian Studies in History and Technology, 2002, 53, 1-78, doi:https://doi.org/10.5479/si.00810258.53.1.

Fujiwara, M., Sun, B., Reale, A., Cimini, D., Larosa, S., Borg, L., von Rohden, C., Sommer, M., Dirksen, R., Maturilli, M., Vömel, H., Kivi, R., Ingleby, B., Kramer, R. J., Demoz, B., Madonna, F., Carminati, F., Lewis, O., Candy, B., Thomas, C., Edwards, D., Noersomadi, Shimizu, K., and Thorne, P.: Justification for high-ascent attainment for balloon radiosonde observationss at GRUAN and other sites, Atmos. Meas. Tech., 2025, 18, 2919–2955, doi:https://doi.org/10.5194/amt-18-2919-2025.

Gallice, A., Wienhold, F. G., Hoyle, C. R., Immler, F., and Peter, T.: Modeling the ascent of sounding balloons: derivation of the vertical air motion, Atmos. Meas. Tech., 2011, 4, 2235-2253, doi:https://doi.org/10.5194/amt-4-2235-2011.

Gong, N., Liu, Y. F., Ren, J., Wu, Q., and Hu, H. L.: A Novel Adaptive Resource Allocation Framework for Sounding Networks, 2021 the 11th International Workshop on Computer Science and Engineering (WCSE 2021) 276-283, doi:https://doi.org/10.18178/wcse.2021.06.040.

Guo, Q. Y., Yang, J. C., Yang, R. K., Qian, Y., and Cao, X. Z.: Evaluation of wind performance of domestic Beidou dropsonde of ball-loading, J. Nanjing Univ. Inf. Eng.: Nat. Sci. Ed., 10, 12, doi:https://doi.org/10.13878/j.cnki.jnuist.2018.05.014, 2018.(in Chinese)

Gong, J. D., Liu, Y. Z., Zhang, L.: A study of simplification and linearization of the NSAS deep convection cumulus parameterization scheme for 4D-Var, Acta Meteorologica Sinica, 2019, 77, 595-616, doi:https://doi.org/10.11676/qxxb2019.048.(in Chinese)

Haig, T. O., and V. E. Lally, 1958: Meteorological Sounding Systems. Bull. Amer. Meteor. Soc., 39, 401–409, doi:https://doi.org/10.1175/1520-0477-39.8.401.

He, Y., Zhu, X., Sheng, Z., and He, M.: Identification of stratospheric disturbance information in China based on the round-trip intelligent sounding system, Atmos. Chem. Phys., 2024, 24, 3839–3856, doi:https://doi.org/10.5194/acp-24-3839-2024.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz - Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, É., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J. - N.: The ERA5 global reanalysis, Q. J. R. Meteorolog. Soc., doi:https://doi.org/10.1002/qj.3803, 2020.

Ingleby, B., and Coauthors, 2016: Progress toward High-Resolution, Real-Time Radiosonde Reports. Bull. Amer. Meteor. Soc., 97, 2149–2161, doi:https://doi.org/10.1175/BAMS-D-15-00169.1.

Ingleby, B., Rodwell, M., Isaksen, L.: Global radiosonde network under pressure, ECMWF Newsletter No. 149 – Autumn 2016, pp. 25 - 30, doi:https://www.ecmwf.int/sites/default/files/elibrary/2016/18147 - global - radiosonde - network - under - pressure.pdf.

Ingleby, B., 2021: Use of radiosonde descent data from ships, ECMWF Newsletter, Page 5 doi:https://www.ecmwf.int/sites/default/files/elibrary/102021/20225-newsletter-no-169-autumn-2021_1.pdf.

Ingleby, B., Motl, M., Marlton, G., Edwards, D., Sommer, M., von Rohden, C., Vömel, H., and Jauhiainen, H.: On the quality of RS41 radiosonde descent data, Atmos. Meas. Tech., 2022, 15, 165-183, doi:https://doi.org/10.5194/amt-15-165-2022.

Johnson, A., Wang, X., Hutchinson, T., and Creus-Costa, J.: Impact of WindBorne observation assimilation on prediction of a TPV merger case from THINICE, J. Geophys. Res. Atmospheres, 2024, 129, e2024JD041395, doi:https://doi.org/10.1029/2024JD041395.

Jensen, M. P., Holdridge, D. J., Survo, P., Lehtinen, R., Baxter, S., Toto, T., and Johnson, K. L.: Comparison of Vaisala radiosondes RS41 and RS92 at the ARM Southern Great Plains site, Atmos. Meas. Tech., 2016, 9, 3115–3129, doi:https://doi.org/10.5194/amt-9-3115-2016.

Liu, S. J., Yang, R. K., Cao, X. Z., Guo, Q. Y., Cheng, K. Q., Kan, Z. P., and Wang, J. C.: Analysis and Numerical Experiment of the Horizontal Drift Round-trip Sounding Balloon's Dynamic and Thermal Process in the Adjacent Space, Chin. J. Atmos. Sci., 2022, 46, 788–804, doi:https://doi.org/10.3878/j.issn.1006-9895.2110.20252.(in Chinese)

Liu, Y. F., Zhou, Y. Y., Du, J. P., Liu, D., Ren, J., Chen, Y. H., Zhang, F., and Chen, J. P.: RTP-GRU: Radiosonde Trajectory Prediction Model Based on GRU, in Proceedings., 2021, 24, 10.1007/978-981-15-8462-6_61.

Liu, L. H.; Han, Y.; Xia, Y. C.; Guo, Q. Y.; Gao, W.; Guo, J. P.: Investigation of Atmospheric Dynamic and Thermodynamic Structures of Typhoon Sinlaku (2020) from High-Resolution Dropsonde and Two-Way Rawinsonde Measurements. Remote Sens. 2022, 14, 2704. doi:https://doi.org/10.3390/ rs14112704.

675 Lau, D.S., Chan, W.S., Wong, Y.C., Lam, C.C., Chan, P.W.: Hindcast Insights from Storm Surge Forecasting of
676 Super Typhoon Saola (2309) in Hong Kong with the Sea, Lake and Overland Surges from Hurricanes
677 Model, Atmos., 2024, 15, 17, doi:https://doi.org/10.3390/atmos15010017.
678 Majumdar, S.J.: A review of targeted observations, Bull. Am. Meteorol. Soc., 2016, 97, 2287-
679 2303, doi:https://doi.org/10.1175/BAMS-D-14-00259.1.
680 Magnusson, L., Majumdar, S.J., Dahoui, M.L., Bormann, N., Bonavita, M., Browne, P.A., Brown, A.R., De
681 Chiara, G., Duncan, D.I., English, S., Geer, A.J., Healy, S., Ingleby, B., McNally, A.P., Pappenberger, F.,
682 Prates, F., Rabier, F., de Rosnay, P., Rennie, M.P., Warrick, F.: The role of observations in ECMWF
683 tropical cyclone initialisation and forecasting, Q. J. R. Meteorolog. Soc., 2025, 151(768),
684 e4924, doi:https://doi.org/10.1002/qj.4924.
685 Pettifer, R. E.: From Observations to Forecasts - Part 2. The development of in situ upper air measurements,
686 Weather, 2009, 64, doi:https://doi.org/10.1002/wea.484.
687 Raman, M. R., Ratnam, M. V., Rajeevan, M., Rao, V. V. M. J., Rao, S. V. B.: Intriguing Aspects of the
688 Monsoon Low-Level Jet over Peninsular India Revealed by High-Resolution GPS Radiosonde
689 measurements, J. Atmos. Sci., 2011, 68, 1413–1423, doi:https://doi.org/10.1175/2011JAS3611.1.
690 Roth, S., & Yoder, C. D.: Balloon missions soar to new heights. Aerospace America, 2022, 60(11), 35-35.
691 doi:https://aerospaceamerica.aiaa.org/year-in-review/balloon-missions-soar-to-new-heights.
692 Ratnam, M. V., Pravallika, N., Babu, S. R., Basha, G., Pramitha, M., Murthy, B. V. K.: Assessment of GPS
693 radiosonde descent data, Atmos. Meas. Tech., 2014, 7(4), doi:https://doi.org/10.5194/amt-7-1011-2014.
694 Seidel, D. J., Berger, F. H., Diamond, H. J., Dykema, J., Goodrich, D., Immler, F., Murray, W., Peterson, T.,
695 Sisterson, D., Sommer, M., Thorne, P., Vomel, H., & Wang, J.: Reference Upper-Air Observations for
696 Climate: Rationale, Progress, and Plans. Bulletin of the American Meteorological Society, 2009, 90(3),
697 361-369. doi:https://doi.org/10.1175/2008BAMS2540.1
698 Shen, Z. P., Pan, X. Z., and Yi, Y. L.: Preparation and properties of modified nano-clay/natural latex composites,
699 J. Rubber Ind., 2020, 67, 4, doi:https://doi.org/10.12136/j.issn.1000-890X.2020.08.0580.(in Chinese)
700 Tan, X. W., Chen, D. H., Zhang, Q. H.: An impact study of a new type of data of adaptive or targeting
701 observation on typhoon forecast, J. Trop. Meteorol., 2006, 22(1), 18 –
702 25, doi:https://doi.org/10.3969/j.issn.1004-4965.2006.01.003.(in Chinese)
703 Vernier, J. - P., Fairlie, T. D., Deshler, T., Ratnam, M. V., Gadhavi, H., Kumar, B. S., Natarajan, M., Pandit, A.
704 K., Raj, S. T. A., Kumar, A. H., Jayaraman, A., Singh, A. K., Rastogi, N., Sinha, P. R., Kumar, S., Tiwari,
705 S., Wegner, T., Baker, N., Vignelles, D., Stenchikov, G., Shevchenko, I., Smith, J., Bedka, K., Kesarkar, A.,
706 Singh, V., Bhate, J., Ravikiran, V., Rao, M. D., Ravindrababu, S., Patel, A., Vernier, H., Wienhold, F. G.,
707 Liu, H., Knepp, T. N., Thomason, L., Crawford, J., Ziemba, L., Moore, J., Crumeeyrolle, S., Williamson,
708 M., Berthet, G., Jégou, F., Renard, J. B.: BATAL: The Balloon Measurement Campaigns of the Asian
709 Tropopause Aerosol Layer, Bull. Am. Meteorol. Soc., 2018, 99, 955–
710 973, doi:https://doi.org/10.1175/BAMS - D - 17 - 0014.1.
711 Vernier, H., Rastogi, N., Liu, H., Pandit, A. K., Bedka, K., Patel, A., Ratnam, M. V., Kumar, B. S., Zhang, B.,
712 Gadhavi, H., Wienhold, F., Berthet, G., and Vernier, J.-P.: Exploring the inorganic composition of the
713 Asian Tropopause Aerosol Layer using medium-duration balloon flights, Atmos. Chem. Phys., 2022, 22,
714 12675–12694, doi:https://doi.org/10.5194/acp-22-12675-2022.

WMO (World Meteorological Organization): 8th WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction and Earth System Prediction, Norrköping, Sweden, 27 - 30 May 2024, doi:https://community.wmo.int/en/meetings/8th-wmo-impact-workshop-home.

Wang, J. H. , Young, K., Hock, T., Lauritsen, D., Behringer, D., Black, M., Black, P. G., Franklin, J., Halverson, J., Molinari, J., Nguyen, L., Reale, T., Smith, J., Sun, B., Wang, Q., Zhang, J. A.: A long-term, high-quality, high-vertical resolution GPS dropsonde data set for hurricane and other studies, Bull. Am. Meteorol. Soc. , 2015, 96, 961-973, doi:https://doi.org/10.1175/BAMS-D-13-00203.1.

WMO (World Meteorological Organization): Guide to Meteorological Instruments and Methods of Observation, Volume III - Observing Systems, WMO-No. 8, 2025 edition, Page 464, pp., doi:https://library.wmo.int/idurl/4/41650.

WMO (World Meteorological Organization): Instruments and Observing Methods Report No. 143: Report of WMO's 2022 Upper-Air Instruments Intercomparison Campaign, Geneva, 2024, 22 pp., doi:https://library.wmo.int/idurl/4/68808.

WMO (World Meteorological Organization): The gaps in the Global Basic Observing Network (GBON), SOFF Series No. 2, 2020, Page 4, pp., doi:https://library.wmo.int/idurl/4/57174.

Wang, D., Wang, J. C., Tian, W. H., Guo, Q. Y.: Quality control and uncertainty analysis of Round - trip drifting sounding system data, Chinese J. Atmos. Sci., 2020, 44, 20, doi:https://doi.org/10.3878/j.issn.1006 - 9895.1912.19203. (in Chinese)

Wang, R. W., Han, W., Tian, W. H., Gong, J. D.: Blacklist Design of AMDAR Temperature Data and Their Application in the CMA-GFS, J. Trop. Meteorol., 2021, 27, 368–377, doi:https://doi.org/10.46267/j.1006-8775.2021.032.

Wang, F., Gong, J. D., Wang, R. C., Chen, Y. D.: A methodological study of the CMA global hybrid four-dimensional variational data assimilation system, Acta Meteorol. Sin., 2024, 82(5), 709–720, doi:https://qxxb.cmsjournal.net/cn/article/doi/10.11676/qxxb2024.20230140. (in Chinese)

Wang, R. W., Wang, J. C., Wang, D., Tao, Y. W., Tian, W. H.: Study on the Influence of Return Sounding Observation System Based on CMA-MESO, Meteorol. Mon., 2023, 49(1), 52–61, doi:https://doi.org/10.7519/j.issn.1000-0526.2022.032601. (in Chinese)

Wang, J. C., Wang, D., Wang, R. W., Tan, J., Rong, N.: Assimilation of Round-Trip Horizontal Drift Radiosonde Data in CMA-MESO 3DVar and Its Impact on Model Forecast, Meteorol. Mon., 2024, 50(2), 50–60, doi:https://doi.org/10.7519/j.issn.1000-0526.2023.110501. (in Chinese)

Wang, J. C., Wang, D., Yang, R. K., Cao, X. Z., Guo, Q. Y.: A Return Radiosonde Trajectory Forecast Method and Its Preliminary Evaluation Based on High Resolution Numerical Weather Prediction Model, Chinese J. Atmos Sci., 2021, 45, 651–663, doi:https://doi.org/10.3878/j.issn.1006 - 9895.2012.20186.

Wen, Q. S., Zhang, X. F., Hu, S., Zhao, P. T., Zhong, S. X., Liu, Z. Y., Zhao, Z. K., Liang, J. H., Dai, G. F., Zhang, C. Z., Li, M. J., Huang, L.: Collaborative assimilation experiment of Beidou radiosonde and drone-dropped radiosonde based on CMA-TRAMS, Atmos. Oceanic Sci. Lett., 2025, 18(2), doi:https://doi.org/10.1016/j.aosl.2024.100555.

Xu, H. F.,Guo, Q. Y., Liu, Y. Z., et al.,: Key factors influencing drift success rate of new-type meteorological balloons, Journal of Applied Meteorological Science, 2025, 36(4), 427-440. doi:https://doi.org/10.11898/1001-7313.20250404.(in Chinese)

Yang, R. K., Wang, Y., and Liu, Q. Q.: Dynamic Performance Analysis of Sounding temperature sensor, Sci. Technol. Eng.,2014, doi:https://doi.org/10.3969/j.issn.1671-1815.2014.04.012.(in Chinese)

Yang, J. C., et al: Research on error prediction technology of radiosonde temperature sensor, Journal of Electronic Measurement and Instrumentation, 2022, 35(12):24-26. doi:https://doi.org/10.13382/j.jemi.B2104288.(in Chinese)

Yang, C. Y., Guo, Q.Y., Cao, X.Z., Zhang, W.: Analysis of gravity wave characteristics in the lower stratosphere based on new round-trip radiosonde. Acta Meteorologica Sinica, 2021, 79(1):150-167. doi:https://doi.org/10.11676/qxxb2021.008.(in Chinese)

Yang, C. Y., Cao, X.Z., Guo, Q.Y., et al. : Feature Extraction and Analysis of Atmospheric Turbulence Based on New Round-Trip Radiosonde [J]. Chinese Journal of Atmospheric Sciences (in Chinese), 2023, 47(6): 1967−1982. doi:https://doi.org/10.3878/j.issn.1006-9895.2202.21103.(in Chinese)

Zhu, H. J., Li, F. Z., Kan, Z. P., He, H., Xiao, D. E., Zhang, L. Q.: Latex balloons buoyancy change analysis and vertical motion trajectory simulation, J. Rubber Ind., 2021, 68(8). doi:https://doi.org/10.12136/j.issn.1000-890-x.2021.01.0017. (in Chinese)

Zhang, X. P., Guo, Q. Y., Yang, R. K., Ma, X. L., Cao, X. Z.: Assimilation Experiment of Rainstorm in the Middle and Lower Reaches of the Yangtze River Based on "ascent - drift - descent" Sounding Data, Meteorol. Mon., 2021, 47(12), 1512–1524, doi:https://doi.org/10.7519/j.issn.1000-0526.2021.12.007. (in Chinese)

Zhou, X. S., Guo Q.Y., Xia Y.C., et al.: Inspection of FY-3D satellite temperature data based on horizontal drift round-trip sounding data. J Appl Meteor Sci, 2023, 34(1): 52-64. DOI: 10.11898/1001-7313.20230105.(in Chinese)

Zhou, X. S., Hong G., Xia Y.C., Luo H.W., Bao W.Z., Tian H.,: Verification of FY-3D Satellite Humidity Profiles Using Descending Phase Data of Round-Trip Drifting Sounding[J].Meteor Mon, 2024, 50(11):1373-1385, http://dx.doi.org/10.7519/j.issn.1000-0526.2024.063002. (in Chinese)

Zhang, C. Z ., et al.,: Application Experiment of Assimilating Beidou Satellite Navigation Round-Trip Sounding Data Observed in Guangdong Province Using CMA-GD Model, Journal of Tropical Meteorology, 2025, 41(1) ,16-25,doi:https://doi.org/10.16032/j.issn.1004-4965.2025.001.(in Chinese)

Zhang, X, Wang Q. P, MA, X.L, et al. ,: The Influence of New Round-Trip Drifting Sounding Observation on the Quality of Numerical Prediction in the Middle and Lower Reaches of the Yangtze River [J]. Chinese Journal of Atmospheric Sciences, 2025, 49(1): 245−256. doi:https://doi.org/10.3878/j.issn.1006-9895.2304.22224.(in Chinese)

Zhang, X. P., Sun, L., Ma, X. L., et al.: Can the Assimilation of the Ascending and Descending Sections' Data from Round-Trip Drifting Soundings Improve the Forecasting of Rainstorms in Eastern China? Atmosphere., 2023, 14, 1127. doi: https://doi.org/10.3390/atmos14071127.

Zhuang, Z. R., Wang, R. C., Wang, J. C., Gong, J. D.: GRAPES_Meso background error characteristics and application, J. Appl. Meteorol. Sci., 2019, 30(3), 316–331, doi:https://doi.org/10.11898/1001-7313.20190306. (in Chinese)

Zhang, X. F., Li, L. X., Yang, R. K., et al.: Comprehensive Marine Observing Experiment Based on High-Altitude Large Unmanned Aerial Vehicle (South China Sea Experiment 2020 of the "Petrel Project"). Adv. Atmos. Sci. 38, 531–537 (2021). doi:https://doi.org/10.1007/s00376-020-0314-1.