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First Rocketsonde Launched from an Unmanned Semi-submersible Vehicle

Hongbin CHEN*[1,2,3], Jun LI[1], Yuejian XUAN[1], Xiaosong HUANG[1], Weifeng ZHU[1], Keping ZHU[4], and Wenzheng SHAO[4]

[1]*Key Laboratory of Middle Atmosphere and Global Environment Observation, Institute of Atmospheric Physic, Chinese Academy of Sciences, Beijing* 100029*, China*

[2]*School of the Earth Science, Chinese Academy of Science University, Beijing* 100049*, China*

[3]*Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing* 210044*, China*

[4]*Jiangxi Xinyu Guoke Technology Co., Ltd, Xinyu* 338018*, China*

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ABSTRACT

The unmanned semi-submersible vehicle (USSV) developed by the unmanned surface vehicle team of the Institute of Atmospheric Physics is an unmanned, rugged, and high-endurance autonomous navigation vessel designed for the collection of long-term, continuous and real-time marine meteorological measurements, including atmospheric sounding in the lower troposphere. A series of river and sea trials were conducted from May 2016 to November 2017, and the first rocketsonde was launched from the USSV. Real-time meteorological parameters in the marine atmospheric boundary layer (MABL) were obtained, including sea surface temperature, and vertical profiles of the pressure, temperature, relative humidity, wind speed, and wind direction. These data are extremely useful and important for research on air–sea interactions, sea surface heat and latent heat flux estimations, MABL modeling, and marine satellite product validation.

Key words: unmanned semi-submersible vehicle, rocketsonde, marine meteorological observation, marine atmospheric boundary layer

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Article Highlights:

- The unmanned semi-submersible vehicle (USSV) is a long-term, unmanned, rugged, and high-endurance autonomous navigation vessel.
- A series of sea trials were conducted and the first rocketsonde was launched from the USSV.
- Real-time marine meteorological parameters were obtained, which are important for research on marine meteorology.

1. Introduction

Meteorology and oceanography require sampling an environment that covers 71% of the surface of the Earth, and traditional observation platforms (e.g., ships, buoys, satellites and aircraft) used to collect meteorological and oceanographic (METOC) data are either expensive or inflexible based on these requirements (Villareal and Wilson, 2014). Relatively slow-moving research vessels cost approximately tens of thousands of dollars a day to operate but can only take snapshots of ocean conditions (Schofield et al., 2010). Moorings with sensors are less expensive than ships but are limited to a given location. Satellite and aircraft-mounted sensors evaluate the air column and ocean surface at a large scale but are limited in their on-scene endurance, real-time sampling data rate, and inability to measure conditions below the sea surface. Hence, researchers urgently require methods to repeatedly gather high-resolution observations over the ocean for an extended duration of time.

Marine unmanned autonomous observation systems include gliders, unmanned surface vehicles (USVs), autonomous underwater vehicles, and unmanned semi-submersible vehicles (USSVs). These systems provide economical, reasonable, and effective methods of marine surveying and ocean exploration, and they are revolutionizing the capacity to monitor the marine environment (Caress et al., 2008; Tang et al., 2011). These marine observation systems can provide opportunities for the acquisition of meaningful METOC data in sea states previously inaccessible to manned survey vessels, e.g., typhoons (hurricanes) and the surrounding extreme sea conditions, and can improve the spa-

* Corresponding authors: Hongbin CHEN
Email: chb@mail.iap.ac.cn

tial and temporal resolutions of METOC measurements (Liquid Robotics, 2016).

The vertical structure of the marine atmospheric boundary layer (MABL) is very important for forecasts of high-impact weather development, such as typhoons (hurricanes) and heavy fog, but it is typically difficult to accurately characterize the MABL, including its spatial and temporal variability, because of both safety considerations and instrument limitations (Franklin et al., 2003; Peng et al., 2016). Dropsondes and rocketsondes are ideal alternatives for the acquisition of boundary layer profiles in remote sea areas and are crucial tools for understanding what is occurring in the low-level troposphere, and in particular within the MABL (Vaisala, 2002; Stern et al., 2016). The cooperation of marine autonomous systems and sounding rockets could be a new way to obtain information regarding the vertical structure of the MABL.

The national boundaries of China encompass a vast sea area, but very few meteorological and hydrological observation sites (islands) and platforms (buoys and vessels) are arranged throughout the oceans. In addition, the number of marine meteorological buoys in China is relatively small; most of these buoys are situated throughout the coastal ocean, while only a small number of mooring buoys are deployed in the deep ocean (Dai et al., 2014). Furthermore, island marine meteorological observation stations and scientific research vessels can acquire continuous METOC measurements, but atmospheric sounding data only two to several times a day (Yang et al., 2015), and they are sparsely distributed in the deep ocean; consequently, their observation data lack spatial representation. As an alternative, the use of long-duration autonomous navigation vehicles, such as mobile marine meteorological observation stations and atmospheric sounding stations, constitutes an efficient, economical, and revolutionary approach to filling gaps in marine meteorological observations throughout the sea area adjacent to China.

This study will focus on USSVs, as this platform is the most relevant to METOC studies that are targeted at obtaining real-time METOC data (including atmospheric sounding data), especially in remote areas or under severe sea conditions. The purpose of this paper is to introduce a USSV and its capability, present the results of USSV applications in marine meteorology, including the first rocketsonde launched from an USSV, and discuss future potential applications of USSVs.

2. USSV introduction and specifications

The technology of marine unmanned autonomous observation systems has evolved over many years. With advances in computer technology and satellite-based navigation and communications, many of the technological roadblocks prohibiting the routine operational use of these systems have been overcome (Wynn et al., 2014). The main technical challenges currently faced by marine unmanned autonomous vehicles are improving their long-endurance persistence and increasing their survivability under extreme sea conditions (US Dod, 2013), which also constitute the main challenges for acquiring long-term marine meteorological observations in the deep ocean. Therefore, to obtain long-term and real-time METOC data, especially in remote areas or under severe sea conditions, the USV team of the Institute of Atmospheric Physics, Chinese Academy of Sciences, has developed a long-endurance unmanned autonomous marine meteorological observation platform. The USSV used in this study is an unmanned, rugged, and high-endurance autonomous navigation vessel designed for long-duration, continuous, and real-time marine meteorological measurement collection, including atmospheric sounding in the lower troposphere. The USSV travels submerged, with only the equipment compartment exposed above the waterline (Fig. 1). This semi-submersible structure minimizes the effect of waves on the vehicle motion, making the USSV very stable. In addition, the center of gravity of the USSV is located in the lower part of the hull, far below its center of buoyancy. This separation allows the USSV to be self-righting after overturning, thereby increasing its survivability under extreme sea conditions. Therefore, the USSV is suitable for acquiring sea surface meteorological and hydrological observations and for launching sounding rockets over large volumes of the ocean, especially in sea states beyond those conventional manned survey ships can withstand. The USSV is 8.0 m long and 1.6 m high, and it has a 1.0 m hull diameter. The vessel has a dry weight (with fuel) of 6200 kg and carries a payload capacity of 300 kg for an automatic weather station (AWS) in addition to computers, METOC sensors, sounding rockets and camera equipment. The USSV is powered by a diesel engine, and it was designed to be continuously operated for 10 days before retrieving the vessel for refueling and retesting. The diesel propulsion system of the vessel can yield a travel range of 3000 kilometers at 8 knots. The main components of the USSV are the frame, equipment compartment, bow, stern and hull. The frame, equipment compartment, and hull are constructed from steel. The bow and stern are made of fiberglass material.

Fig. 1. The first USSV sea trial conducted in Bohai Bay near the port of Jingtang on 13 June 2017.

The USSV-based marine meteorological observation system is composed mainly of a marine system and a ground system (Fig. 2). The USSV can be preprogrammed before a mobile or station-based mission, or it can have the program changed during the mission. The autonomous navigation and control system of the USSV can control vessel operation, data transmission and rocket launches via real-time bidirectional radio frequency communication or a continuous BeiDou navigation satellite system/Iridium satellite communication link. The sensor platform of the USSV is equipped with a standard weather station to measure the air temperature, humidity, pressure, wind speed, and wind direction at 1.5 m above the sea surface. Two sea surface temperature (SST) sensors are located on the hull at a nominal depth of 0.2 m. The sampling frequency of the data is 1 Hz. The observation data are averaged over a 1-min window and then transmitted back to a ground station through BeiDou navigation satellite communication systems. The air temperature, relative humidity (RH), and barometric pressure sensors of the weather station and the seawater temperature sensors are all calibrated before conducting sea trials. The standard weather station installed on the USSV is the Airmar 200WX weather station, which is an all-in-one weather sensor equipped with an internal GPS engine and a three-axis solid-state compass. The true wind speed and direction can be calculated on the moving vessel without the need to add any additional sensors. The wind measurements are highly accurate and stable under most sea conditions, even if the vessel is pitching and rolling up to 30° in rough seas (Airmar, 2013).

The rocketsonde used in this study, which is essentially a rocket-deployed dropsonde, was designed in cooperation with Jiangxi Xinyu Guoke Technology Co., Ltd., to meet the requirements for detecting the detailed vertical structure of the low-level troposphere at sea. The USSV-launched rocketsonde data can be used to determine the refractivity conditions that affect the performance of radar and microwave communication. The air temperature, humidity, and pressure are measured directly by sensors at approximately 1 Hz, and wind speed and wind direction are calculated through GPS/BeiDou tracking data. The vertical resolution of rocketsonde data is dependent on the parachute-aided descent speed (approximately 4–5 m s^{-1}), rate of data transmission, and sensor response time (dependent on the ambient temperature). When the temperature is above freezing, the vertical resolution will typically be 4–5 m. There are two types of sounding rockets used in this study, and their maximum sounding heights are 1.3 km and 6 km. The USSV can carry up to 48 sounding rockets, which can be launched through either a preset command or a real-time command, and the data are transmitted to a vessel-based receiving station.

3. USSV trial results

From May 2016 to May 2017, a series of preliminary trials was conducted on the Huaihe River in Huainan city, Anhui Province. The purpose of these experiments was to validate the hull structure of the USSV and the performance of its subsystems. The main vessel control computer and observation equipment were not installed. The USSV was controlled by the automation programmable logic controller (APLC) on the vessel, and the APLC was remotely operated via radio communication from a remote control. The USSV was launched into the water with the aid of a truck crane. Then, the engine was run and a navigation test was performed along the main channel of the Huaihe River. The ballasting and basic engine and control functionalities of the vessel were verified, and most subsystems worked well.

The first sea trial was conducted in Bohai Bay near the port of Jingtang on 13 June 2017, with the objectives of verifying the performance of the USSV and its ability to function as an unmanned mobile platform for marine meteorological observation in the ocean. The main vessel control computer,

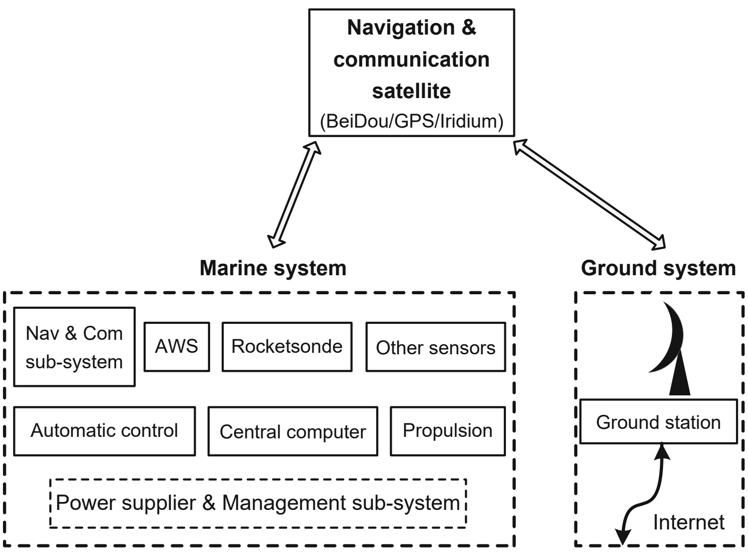

Fig. 2. Block diagram of the USSV-based marine meteorological observation system.

AWS, sounding rocket, and SST sensors were installed. The USSV was deployed with a truck crane at the dock and towed into the harbor. The vehicle left the harbor via radio control and then navigated following the routes set by the satellite communication system. The navigation and control system, bidirectional radio/satellite communication system, automatic and command launching of the rocketsonde, and waterproof and salt-resistant performances of the USSV were tested and all worked well. The second sea trial was conducted in the same sea area on 9 November 2017. The sea trials tested and verified most of the basic functions of the USSV and identified issues to be addressed. The hydrostatic design of the hull was good, and the vessel displayed strong righting torque. Additionally, the propulsion system was very stable. The diesel engine ran well and provided sufficient power. The average speed of the USSV was approximately 6 knots, and the maximum speed was 9 knots. The navigation and control system worked well, the position feedbacks were accurate and reliable, and the USSV sailed along the set routes (Fig. 3).

The AWS and SST sensors all worked well, and the measurement data were transmitted in real time via Beidou satellite communication systems to the ground station. Figures 4 and 5 show time series of the observed major METOC parameters collected by the USSV on 13 June and 9 November. During the first sea trial (Fig. 4; 13 June 2017), the air temperature and SST significantly decreased and the RH increased after the USSV departed the port at 1430 LST. These changes were very small when the vehicle conducted voyage tests in the open sea, eventually returning to the port at 1620 LST. The wind remained southerly during the entire sea trial, and the average wind speed in the open sea was 5.1 m s^{-1}, which was significantly higher than that (2.8 m s^{-1}) at the port. The atmospheric pressure slightly dropped overall, excluding a small increase at approximately 1540 LST. The average SST was 2°C higher than the air temperature. During the second sea trial (Fig. 5; 9 November 2017), the air temperature, RH, atmospheric pressure, and wind speed exhibited the same trends as observed during the first sea trial, but the differences between the observations in the harbor and the open sea were more pronounced. The maximum SST and wind speed (13.2°C and 9.0 m s^{-1}) in the open sea were significantly higher than those (11.3°C and 2.1 m s^{-1}) in the harbor.

Four meteorological sounding rockets were successfully launched from the USSV via preset and real-time commands issued with the satellite communication system during the first sea trial. The maximum detectable height of the rockets reached 1230 m, and high vertical resolution measurements of the air temperature, RH, pressure, wind direction, and wind speed data were obtained in quasi-real time. Rocket sounding data were transmitted in real time via satellite communications to the ground station. Figure 6 shows the results for a rocket launched at 1515 LST 13 June 2017. The profile contains two temperature inversion layers, which were detected at the heights of 42 m and 1120 m. The RH below these inversions was significantly lower than that in the inversions. The MABL height was evaluated according to the location of the maximum gradient of the potential temperature (θ) profiles and the base of an elevated temperature inversion (Seidel et al., 2010). The estimating MABL height was 1120 m. In the MABL, the wind direction gradually shifted from southerly to easterly, and the wind speed slowly decreased with height. Three sounding rockets were successfully launched from the USSV during the second sea trial. Figure 7 shows the results for a rocket launched at 1148 LST 9 November 2017. An elevated temperature inversion was detected, and the estimated MABL height was 312 m. The RH was high, and its vertical distribution was uniform. Additionally, the changes in wind direction and wind speed were small in the MABL. Above the MABL, the RH obviously decreased, and the wind speed rapidly increased.

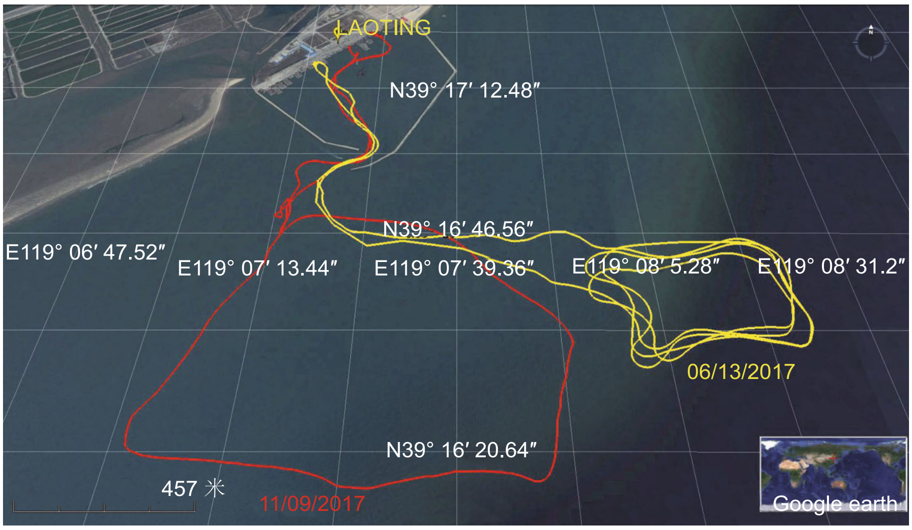

Fig. 3. Map of the trajectories of the two USSV sea trials in Bohai Bay in 2017. The yellow and red tracks represent the routes on 13 June and 9 November, respectively.

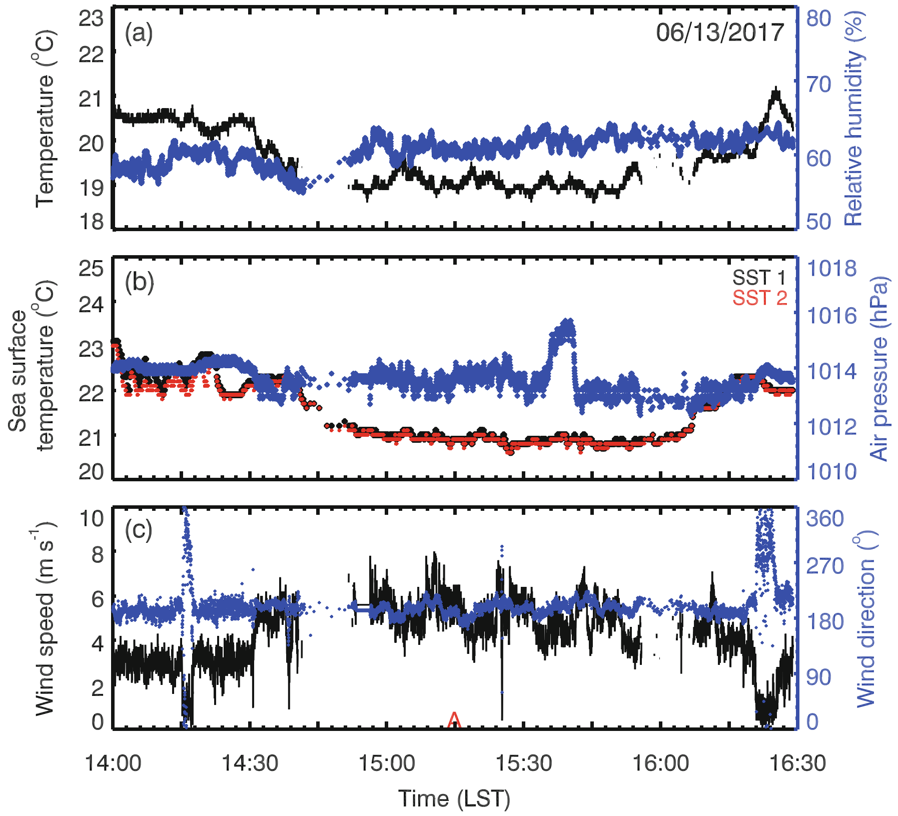

Fig. 4. Time series (LST) of (a) air temperature and RH, (b) SST and atmospheric pressure, and (c) wind direction and wind speed, collected onboard the USSV on 13 June 2017. The red triangle represents the sounding rocket launch time.

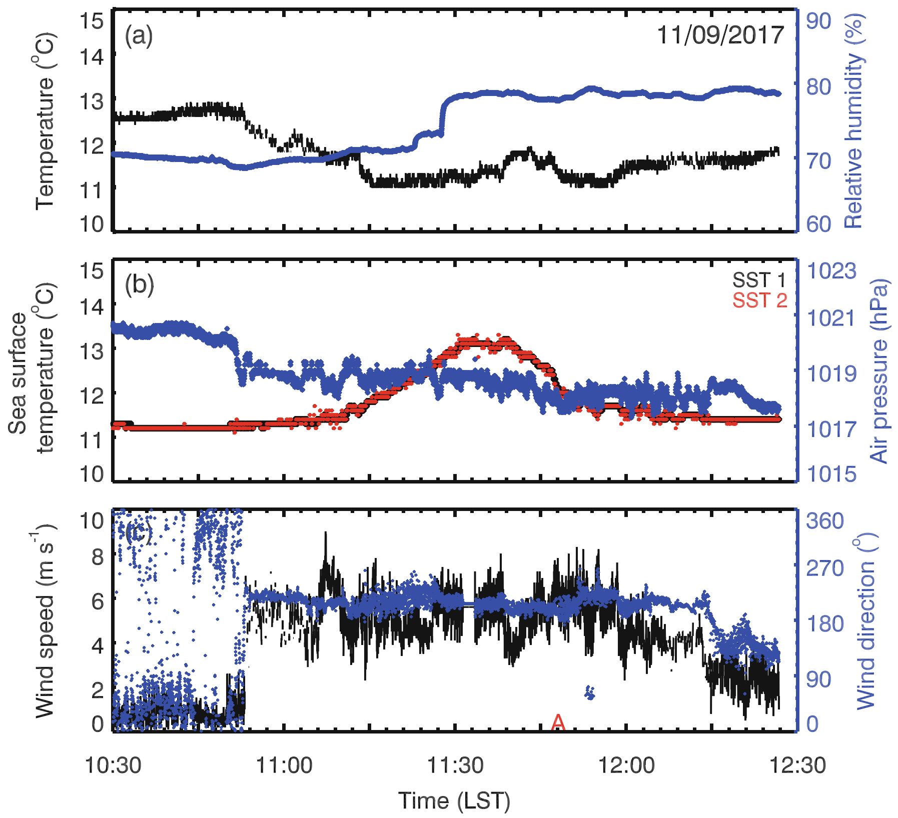

Fig. 5. Similar to Fig. 4 but for the METOC data obtained on 9 November 2017.

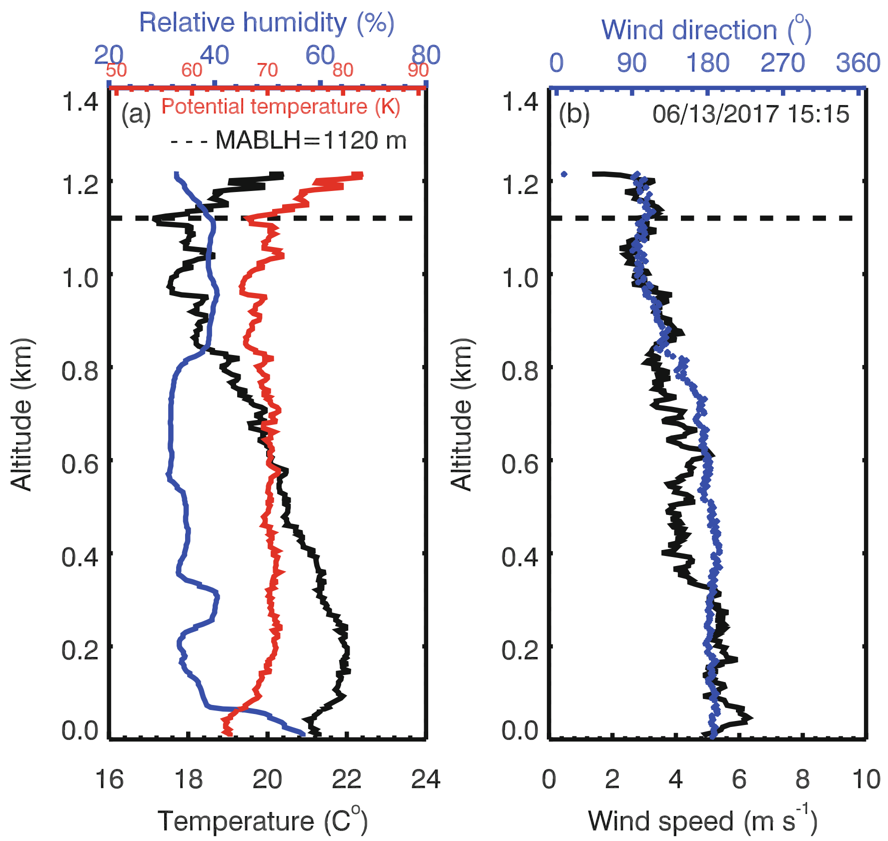

Fig. 6. Profiles of temperature, RH, θ, wind direction, and wind speed measured by rocketsondes on 13 June 2017. The dashed black horizontal line represents the top of the MABL.

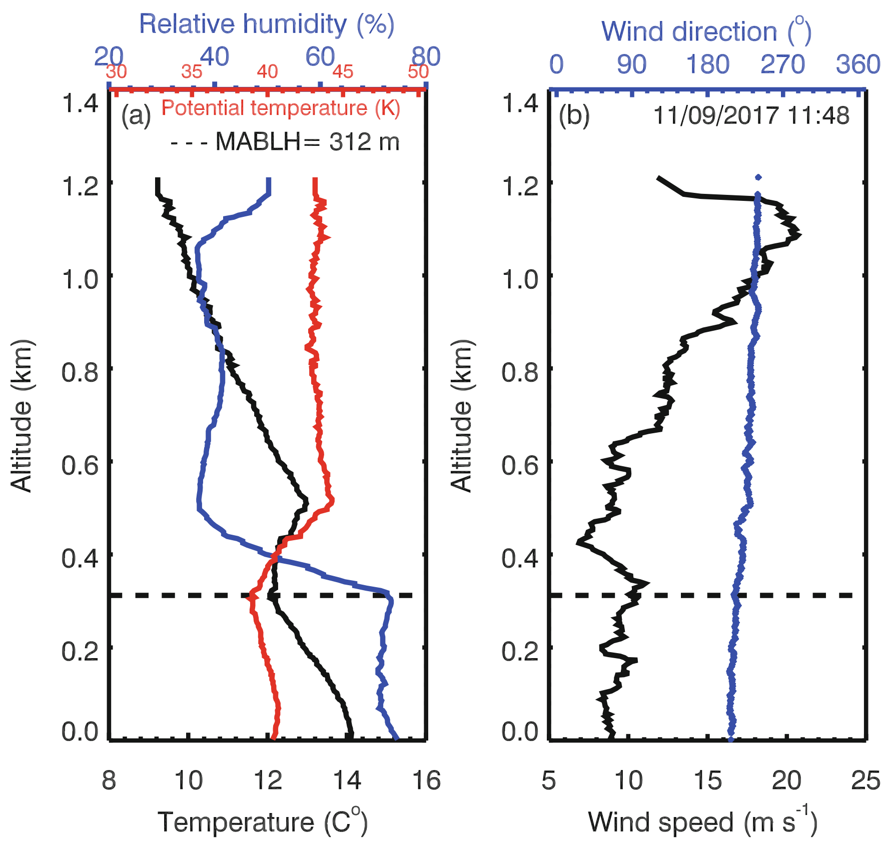

Fig. 7. Similar to Fig. 6 for rocketsonde data obtained on 9 November 2017.

4. Future work

The future of METOC monitoring and research requires the cooperation of many autonomous unmanned vessels and METOC instruments. Long-duration vessels that can survive under extreme sea conditions and can be flexibly deployed will play an important role in future METOC research and allow researchers to more effectively utilize autonomous unmanned vessels and METOC sensors to continuously observe the ocean. Many METOC questions concern the sea–air interface; therefore, it is necessary to obtain both vertical profiles in the low-level atmosphere and vertical profiles in seawater. The new generation of USSVs can carry various sensors relevant to marine science, including conductivity–temperature–depth, acoustic Doppler current profiler, and motion sensors, which can provide vertical profiles of the conductivity, water temperature, current velocity, and wave height and direction. A new interconnected USSV METOC observation network system will improve the efficiency of collecting METOC observations and provide comprehensive data at the temporal and spatial scales required to answer relevant scientific questions.

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