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IAP's Solar-Powered Unmanned Surface Vehicle Actively Passes through the Center of typhoon Sinlaku (2020)

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ABSTRACT

The solar-powered marine unmanned surface vehicle (USV) developed by the USV team of the Institute of Atmospheric Physics is a rugged, long-duration, and autonomous navigation vessel designed for the collection of long-range, continuous, real-time, meteorological and oceanographic measurements, especially under extreme sea conditions (sea state 6–7). These solar-powered USVs completed a long-term continuous navigation observation test over 26 days. During this time, they coordinated double-USV observations and actively navigated into the path of Typhoon Sinlaku (2020) before collecting data very close to its center during the 2020 USV South China Sea Typhoon Observation Experiment. Detailed high temporal resolution (1 min) real-time observations collected by the USV on the typhoon were used for operational typhoon forecasting and warning for the first time. As a mobile meteorological and oceanographic observation station capable of reliable, automated deployment, data collection, and transmission, such solar-powered USVs can replace traditional observation platforms to provide valuable real-time data for research, forecasting, and early warnings for potential marine meteorological disasters.

Key words: solar-powered unmanned surface vehicle, typhoon, meteorological and oceanographic observation

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1. Introduction

Tropical cyclones, including typhoons and hurricanes, are among the most destructive natural phenomena impacting ocean and coastal regions. China has a vast sea area, a long coastline, and developed coastal regions. Coincident with the development and utilization of the oceans, maritime transportation, fish farming, oil and gas explorations, scientific research and tourism activities are occurring more frequently. However, the weather in China's coastal regions and adjacent seas is highly variable, and marine meteorological disasters, such as typhoons, heavy rains, strong winds, storm surges, heavy fog, and intense moist convection at sea, often occur (Xu et al., 2009; Yu et al., 2012). China is among the countries most affected by tropical cyclones worldwide, with approximately seven typhoon landfalls along the southeast coast of China each year, causing direct economic losses of approximately 0.4% of the gross domestic product (GDP), more than 9,000 casualties, and more than 500 deaths (Lei, 2020).

Many studies have aimed at improving our understanding of the genesis and evolution of typhoons and hurricanes (Black et al., 2007; Sanford et al., 2007; Bell et al., 2012), consequently, the track forecasting of typhoons has significantly

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improved in recent decades. However, the forecasting of typhoon genesis, intensification, and change in track direction are still subject to a high degree of uncertainty (Bender et al., 2007). In particular, errors in model initialization, caused by the lack of real-time marine meteorological observations, especially in remote sea areas, is one of the main reasons for the uncertainty in typhoon forecasting (Feng et al., 1999; Committee on Atmospheric Science and Climate et al., 2008; Ito and Wu, 2013; Rogers et al., 2013; Emanuel, 2018). Over the past two decades, China's meteorological, oceanographic, scientific and maritime departments have installed several automated weather stations on offshore manned and unmanned islands, and on oil and gas platforms, in addition to the dozens of marine buoys that have been deployed along the coast. Some meteorological and oceanographic observation data have been obtained during the passage of typhoons, and case studies of typhoons have revealed meteorological and oceanographic characteristics of their development. (Yang et al., 2015; Chen et al., 2019a). However, the number of meteorological and oceanographic observing platforms and buoys deployed along coastal regions of China is still small, and very few are deployed in the deep ocean (Dai et al., 2014). This situation limits the improvement of marine meteorological and hydrological forecasting, especially for typhoon forecasting. Therefore, it is necessary to develop advanced observation technology and equipment to help fill the data gaps (Eckman et al., 2007). With advances in satellite communication, navigation technology, and computer technology, breakthroughs have been made in recent years regarding the research and application of marine unmanned autonomous observation systems (Lenan and Melville, 2014; Wynn et al., 2014).

To obtain long-term and real-time meteorological and oceanographic observations, especially during the passage of typhoons, the Institute of Atmospheric Physics (IAP) of the Chinese Academy of Sciences developed a solar-powered, long-endurance, marine, unmanned, and autonomous meteorological observation platform. The solar-powered unmanned surface vehicle (USV) passed through the center of Typhoon Sinlaku (2020) on 1 August, 2020 and successfully collected real-time data of the typhoon that are valuable for typhoon research and forecasting.

In this paper, we introduce the IAP USV and its onboard instrumentation. We then briefly describe Typhoon Sinlaku (2020) and the USV typhoon observation experiment and present preliminary results. In the final section, we summarize our findings and discuss future potential applications of USVs.

2. Introduction to IAP USV and specifications

The main technical challenges faced by USV in acquiring long-term meteorological and oceanographic observations in the deep ocean include improving its long-term persistence and increasing its survivability under extreme sea conditions, especially during the passage of typhoons/hurricanes (US DOD, 2013). Therefore, the IAP USV team developed two types of long-term unmanned autonomous marine meteorological observation USVs, which are the solar-powered USV and the diesel-powered unmanned semi-submersible vehicle (USSV). From 2017 to 2020, the USV and USSV have completed dozens of sea tests and trials, and have sailed thousands of kilometers in total. The world's first rocketsonde was launched from the USSV in 2017 (Chen et al., 2019b). The IAP USV is a long-term, rugged, and unmanned autonomous navigation vessel (Fig. 1). The USV can automatically deploy, collect and transmit observations, and can complete unmanned measurements under extreme sea conditions. Details about the USV design and performance are provided in Table 1. The vessel can carry a payload of 20 kg for an automatic weather station (AWS), sea surface temperature (SST) and seawater salinity sensors, wave sensors, and pyranometers. China's Beidou communication satellites allow for the measured data to be automatically transmitted to the ground control center, where high temporal resolution temperature, humidity, air pressure, wind direction, wind speed, SST, seawater salinity, and total shortwave radiation can be obtained in real-time. The technical specifications of meteorological and hydrological sensors are shown in Table 2.

Compared with traditional meteorological and oceanographic observation platforms such as buoys, the main technical advantages of the USV are as follows:

(1) Automatic deployment, collection, and transmission of data.

(2) Powered by solar energy, the USV can carry out long-term and long-range continuous meteorological and oceanographic observations.

(3) The semi-submersible structure minimizes the effect of waves on vehicle motion, making the USV very stable and allowing it to survive and collect data under extreme sea conditions (sea state 6–7).

(4) Real-time acquisition and Beidou satellite transmission of high temporal resolution (up to one minute) observations.

The main components of the USV system are the USV hull, USV control system, power system, communication system, meteorological and hydrological observation loads, auxiliary unit, and a ground control center. A block diagram of the system is shown in Fig. 2. The meteorological and hydrological sensors were calibrated before and after the observation experiment. The USV can be self-righting, semi-submerged, and has a high waterproof grade, and can work under severe sea conditions (sea state 6–7). The onboard control system can preset and change the navigation route and observation mode via presets and real-time commands issued with the communication system from the ground control center. The communication system transmits control commands and observation data in real time through the Beidou satellite array. The

Fig. 1. The IAP solar-powered USV conducted sea trials in a sea area near Tanmen Port of Hainan Island in June 2020.

Table 1. Main technical parameters of the solar-powered USV.

Technical parameters	The solar-powered USV
Observation modes	Navigation mode, positioning mode, drifting mode
Weight	80 kg
Size	4.6 m×2.0 m×1.2 m
Speed	3–5 knots
Endurance	30 days
Positioning accuracy	10 m
Payload	20 kg
Communication	Beidou satellite communication
Data interface	USB/RS232
Power	Solar energy/24 V
Power consumption	400 W
Sea states	6–7
Communication frequency	1–60 mins (adjustable)
Observation parameters	Temperature, humidity, air pressure, wind direction, wind speed, SST, salinity, and total shortwave radiation

Table 2. Technical specifications of the meteorological and hydrological observation parameters.

Observation parameters	Technical specifications (range and accuracy)
Temperature	−25°C–55°C, 0.2°C
Air pressure	850–1150 hPa, 0.5 hPa
Relative humidity	0–100%, ±3%
Wind speed	0–40 m s^{-1}, 1 m s^{-1}
Wind direction	0°–360°, 2°–5°
Total shortwave radiation	0–2000 W m^{-2}, 3%
Seawater temperature	−5°C–35°C, 0.01°C
Conductivity	0–80 mS cm^{-1}, 0.01 mS cm^{-1}

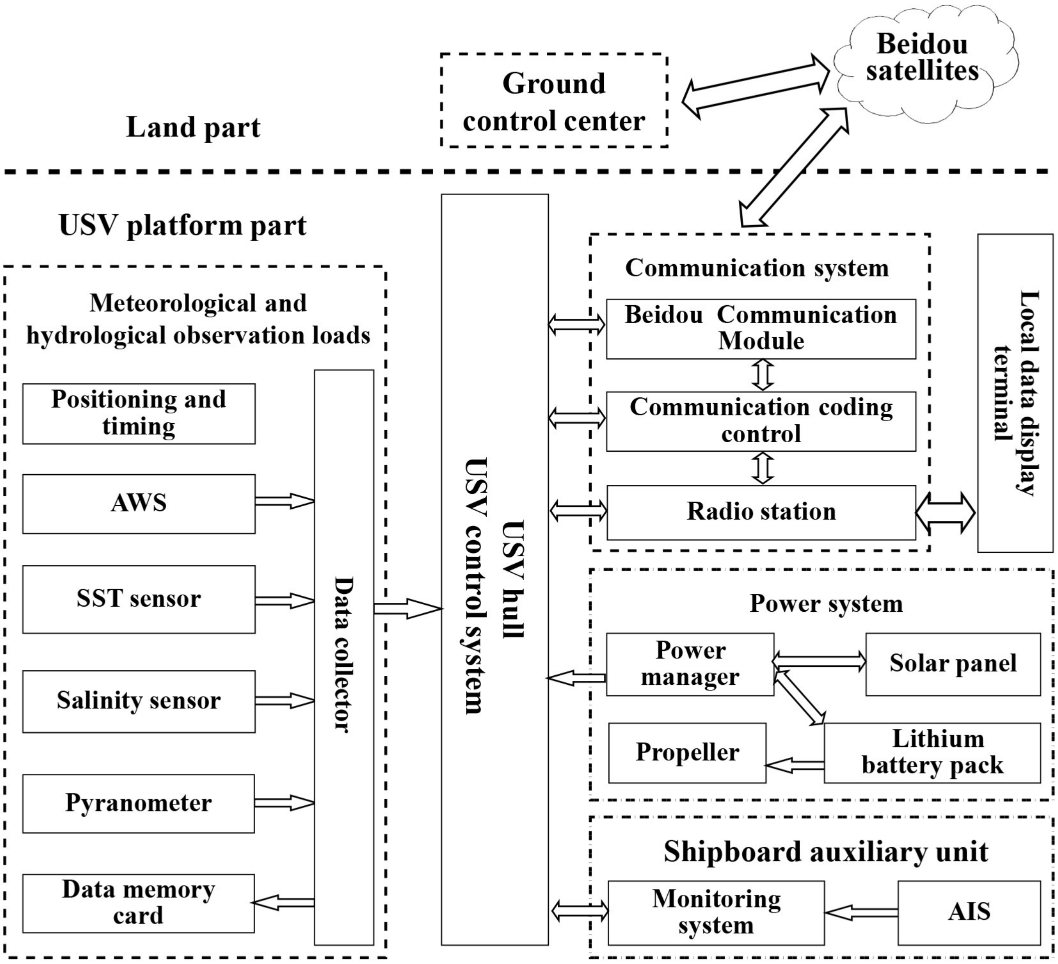

Fig. 2. Block diagram of the USV meteorological and oceanographic observation system.

USV platform can carry different types of meteorological and oceanographic observation instruments according to the observation mission. The ground control center monitors the working state of the USV in real time, sends control commands, and receives and stores observation data.

3. Typhoon Sinlaku (2020)

A tropical depression formed in the South China Sea within the Northwestern Pacific Ocean basin at 0700 UTC on 31 July, 2020. The tropical depression strengthened into Typhoon Sinlaku (2020) at 0700 UTC on 1 August, 20 kilometers west of the coastal city of Sanya, which is located on the south China island province of Hainan. The typhoon center swept over south of Hainan Island while moving northwestward at a speed of 25 kilometers per hour, before heading into the Beibu Gulf. Sinlaku (2020) made a landfall along the coast near Thanh Hoa City, Vietnam, at 0840 UTC on August 2 with winds reaching up to 18 m s^{-1} and a measured pressure of 992 hPa before being downgraded to a tropical storm. The wind was not overly strong, but the typhoon was large, and the central dense overcast extended over a wide area. Typhoon Sinlaku (2020) brought heavy rainfall to some areas in southern China, northern Thailand, and northern Vietnam from July 31 to August 3.

4. USV typhoon observation experiment and results

During May–August 2020, the IAP's USV team carried out typhoon observation experiments and preliminary tests in the South China Sea with its base located at Tanmen Port in Qionghai City, Hainan Island. The 2020 USV South China Sea Typhoon Observation Experiment is an important part of the "South China Sea Experiment 2020" or "Petrel Project", led by the Meteorological Observation Center of the China Meteorological Administration (CMA). The "Petrel Project" involved a variety of observation platforms, such as unmanned aerial vehicles (UAVs), marine USVs, drifting buoys, and intelligent reciprocating horizontal drifting radiosonde systems and satellites, to conduct comprehensive three-dimensional field observation experiments over the South China Sea. In the preliminary test phase, the IAP USV completed the shore test, the nearshore test, and the offshore test, as well as the long-term, continuous navigation observation test over a period of 26 days, with a total navigation of more than 1100 km. Additionally, a coordinated observation of double USVs was conducted continuously for a week. A series of tests, during the preliminary test phase, verified that the USV is capable of stable operation over a long period and that the multiple USVs can perform coordinated observations with collision prevention in the marine environment, which laid the foundation for the typhoon observation experiment in the deep ocean.

On 22 July, 2020, in coordination with the "Petrel Project", a USV was deployed from Tanmen Port of Hainan Island to participate in the South China Sea Typhoon Observation Experiment. The track of the USV from 22 July to 4 August, 2020, is shown in Fig. 3. On 23 July, the USV arrived at the UAV observation sea area, 96 kilometers away from Tanmen Port, and conducted positioning observations (Fig. 3b). In conjunction with the pre-experiment of UAV observations, the USV sailed to the sea area below the UAV route and conducted observations on 24 July. From 24 to 26 July, the USV carried out drifting-returning-fixed-point observation tests in the positioning sea area to improve the efficiency of the electric energy utilization of USVs for the purpose of achieving long-term, quasi-fixed-point observations. The trajectory of the USV in the positioning sea area is shown in Fig. 3c. During the quasi-fixed-point observation test, the USV drifted approximately 13–15 km at night and returned to the positioning point in 4–5 hours against the currents; 78.0%, 61.3%, and 55.3% of the time, the USV was within 10, 5, and 3 km of the positioning point, respectively. On 26 July, the USV sailed southeast to conduct a deep-sea observation test, and at 0803 LST 29 July, it reached the farthest point in this experiment, which was 176.6 km away from Tanmen Port and 151.5 km away from the coast of Hainan Island. The USV continued to sail in the northwest direction before returning to the fixed point on 30 July.

The meteorological and oceanographic sensors all worked well from 22 to 30 July, and the measurement data per minute were transmitted in realtime via the Beidou satellite communication system to the ground station, with a data integrity rate of 89.7%. The environmental conditions measured by the USV during the typhoon observation experiment are shown in Fig. 4. Before the USV approached the typhoon system, the air temperature and relative humidity showed obvious diurnal changes and negative correlations, while the air pressure, SST, and salinity also showed diurnal changes, but these variation ranges were small. After the USV reached the UAV observation sea area on 23 July, southerly and southwesterly winds were dominant, with an average wind speed of 4.1 m s^{-1} and a maximum wind speed of 10.4 m s^{-1}. On 29 July, the wind gradually strengthened and changed from southerly to northerly. The air temperature, air pressure, SST, and salinity gradually decreased. The total solar radiation observations showed that this period was characterized by both sunny and cloudy conditions. On 31 July, the USV approached the typhoon system, with dramatic changes in air temperature, pressure, and wind speed. The maximum measured wind speed was 15.1 m s^{-1}. Unfortunately, on 31 July, the humidity sensor stopped working.

On 31 July 2020, the Central Meteorological Observatory (CMO) of the CMA predicted that a tropical depression would strengthen into a typhoon [named Sinlaku (2020)] and move in a northwesterly direction close to Hainan Island, at

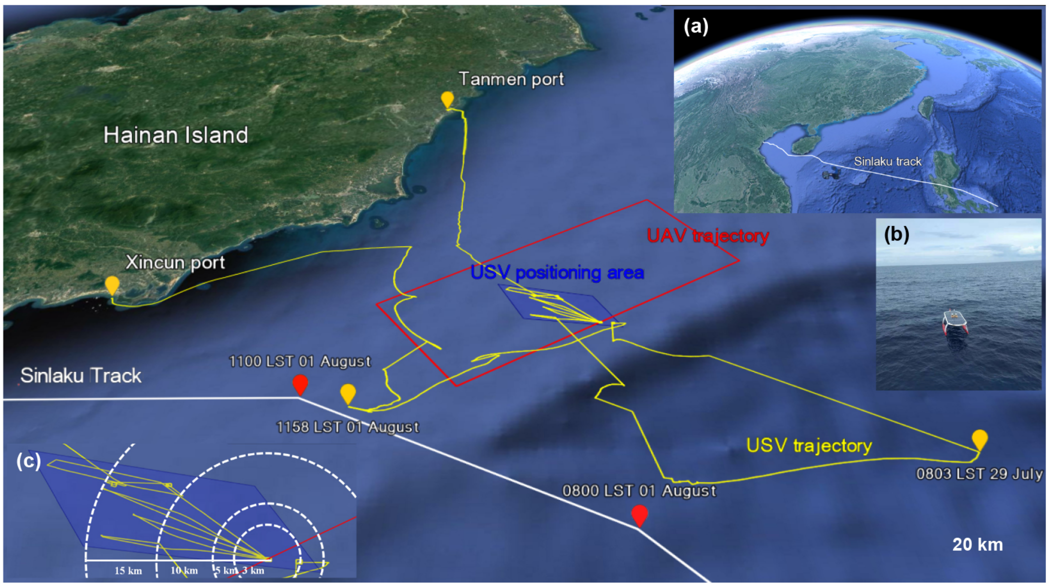

Fig. 3. Map of the trajectory of the USV during the USV South China Sea typhoon observation experiment from 22 July to 4 August 2020. The yellow, white, and red trajectories represent USV routes, Typhoon Sinlaku (2020) track, and UAV routes, respectively. (a) Track of Typhoon Sinlaku (2020) is shown. (b) The USV sailing in the South China Sea. (c) The trajectory of the USV positioning in the sea area.

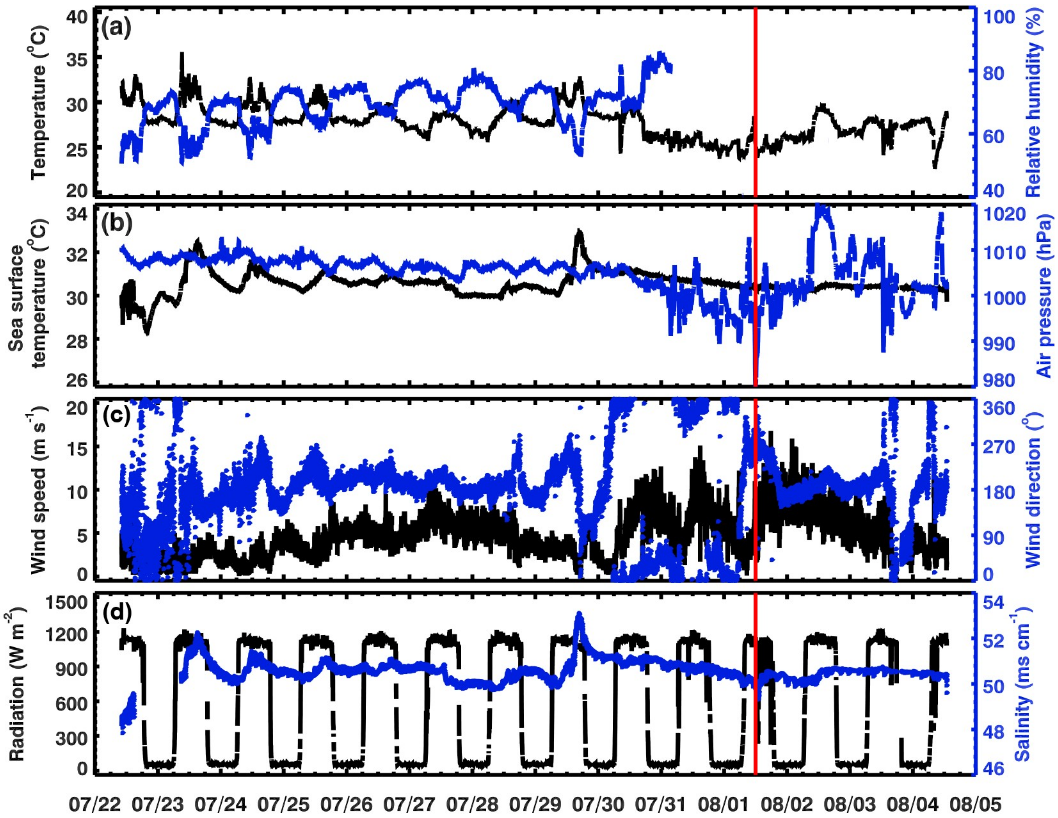

Fig. 4. Time series (LST) of (a) air temperature and relative humidity, (b) SST and atmospheric pressure, (c) wind direction and wind speed, and (d) total shortwave radiation and seawater salinity collected onboard the USV during the USV South China Sea typhoon observation experiment from 22 July to 4 August 2020. The solid red lines represent the times that the USV was close to the center of Typhoon Sinlaku (2020).

which time the USV was approximately 30 km away from the forecasted path of Sinlaku (2020). The USV then sailed at full speed to the sea area where Sinlaku (2020) was expected to pass through and arrived at the area at 0928 LST on 1 August, 2020. The environmental conditions measured by the USV on 1 August are shown in Fig. 5. At 1158 LST, the USV successfully passed through the center of Typhoon Sinlaku (2020), which is about 2.4 km from the typhoon path issued by the CMO. At 0900 LST on 1 August, typhoon observation data were provided by the IAP's ground control center to the operational Typhoon and Marine Weather Prediction Center of the CMO in real time. This was the first time that USV observation data were used for operational typhoon warning and forecasting.

Within the experiment, the IAP solar-powered USV actively navigated towards the path of Typhoon Sinlaku (2020) and successfully collected measurements on air and sea conditions at 1 min intervals and transmitted them in real time to the ground control center before being forwarded to an operational typhoon forecast center. According to our knowledge, this is the first time such achievements were accomplished by a USV, providing valuable data that traditional observation platforms could not provide, that have the potential for improving both the research and forecasting of typhoons as well as other types of weather over ocean.

5. Summary and future work

As part of the USV South China Sea Typhoon Observation Experiment, a solar-powered USV developed by IAP of CAS completed a long-duration (26 days), continuous navigation observation test. It coordinated observations with double USVs and the USV typhoon observation experiment in the deep ocean, which verified and demonstrated that this USV is capable of long-duration, long-range, and stable operations, and that it can safely perform multi-USV coordinated observations while being resilient to typhoon-strength sea conditions.

Typhoon development involves air-sea interactions throughout the entire typhoon system; therefore, it is necessary to deploy multiple USVs to obtain sea-surface meteorological and oceanographic data and seawater temperature and salinity profiles in the upper ocean. The new generation solar-powered USVs can also carry other sensors relevant to marine science, including wave sensors, conductivity-temperature-depth sensors, and acoustic Doppler current profilers that can provide vertical profiles of the conductivity, water temperature, current velocity in the upper ocean, as well as, sea surface wave height

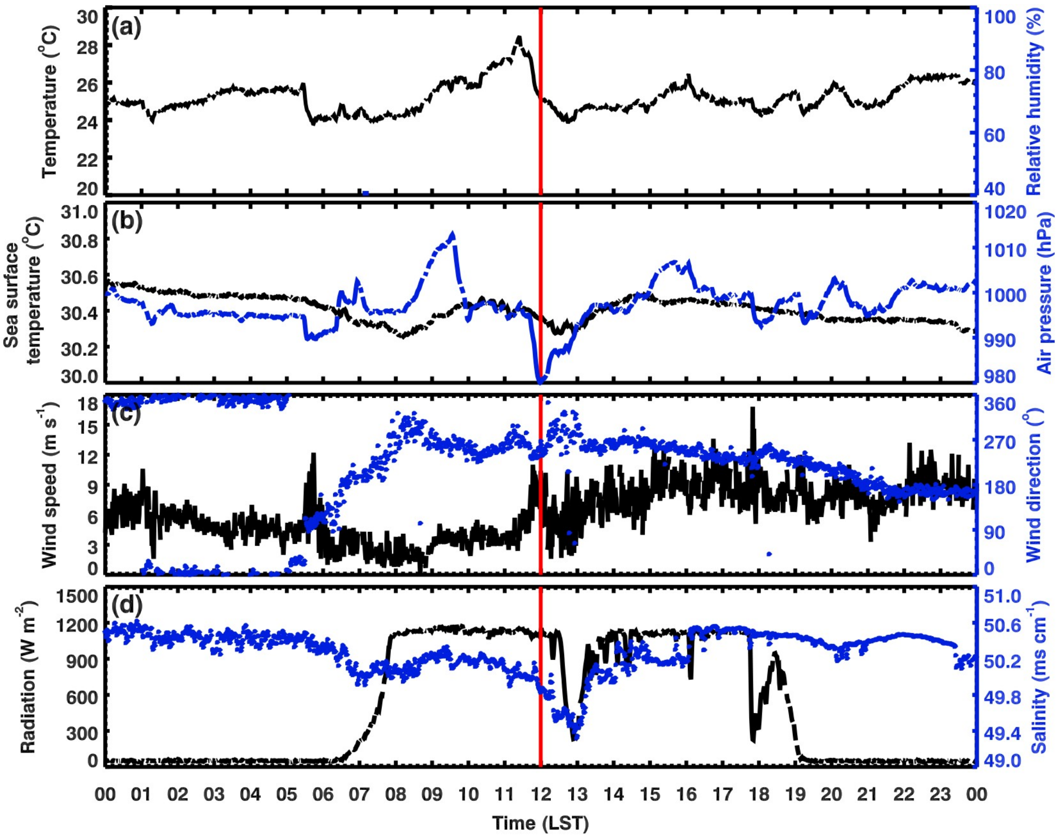

Fig. 5. Time series (LST) of (a) air temperature and relative humidity (the humidity sensor stopped working), (b) SST and atmospheric pressure, (c) wind direction and wind speed, and (d) total shortwave radiation and seawater salinity collected onboard the USV during Typhoon Sinlaku (2020) passage on 1 August 2020. The solid red lines represent the time that the USV was close to the typhoon center.

and direction. A multiple USV observation network can provide comprehensive meteorological and oceanographic data at temporal and spatial resolutions required for research, forecasting, and early warnings for many types of marine meteorological disasters. Further development, testing, and application of solar-powered USVs and related instruments should continue.

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