Tracking Ocean Currents and Surface Temperature in Segara Anakan Lagoon using Drifting Buoy

Isnaini Prihatiningsih[1*], Rizqi Rizaldi Hidayat[1], Iqbal Ali Husni[1], Agung Tri Nugroho[1], Mukti Trenggono[1], Jatnika Jatnika[1], Syarief Hidayat[2]

[1]Department of Marine Science, Faculty of Fisheries and Marine Science, Jenderal Soedirman University
Jl. Prof. Dr. HR. Boenjamin 708, Purwokerto, Jawa Tengah 53122, Indonesia
[2]College of Oceanography and Ecological Science, Shanghai Ocean University
Shanghai 201306, China
Email: isnaini.prihatiningsih@unsoed.ac.id

Abstract

Ocean currents and sea surface temperature (SST) were recognized as key oceanographic parameters that played a crucial role in understanding coastal and marine physical processes. Despite their importance, real-time monitoring of these variables in narrow and dynamic waterways remained limited. This study designed, developed, and evaluated a low-cost drifting buoy system for the real-time measurement of ocean currents and SST. The buoy integrated temperature sensors and a Global Positioning System (GPS) module, with LoRa technology enabling reliable long-range data transmission. GPS validation revealed a positional error of only 1–2 meters, even in challenging environments with dense urban or vegetative obstructions. Temperature sensor calibration against a standard thermometer yielded an R^2 value of 0.9989, indicating an exceptionally strong correlation. Field measurements in Segara Anakan Lagoon recorded SST values that fluctuated between 28.5°C and 29.37°C, reflecting typical tropical coastal conditions. Current speeds ranged from 0.052 to 0.78 m/s, with a distinct tidal influence: flows moved landward into the estuary during high tide and seaward during low tide. The results confirmed that the buoy was an effective, accurate, and practical tool for nearshore oceanographic monitoring, particularly in remote or data-scarce regions.

Keywords: Drifting Buoy, Ocean Current, Sea Surface Temperature, Segara Anakan Lagoon

INTRODUCTION

Ocean currents, defined as the horizontal movement of seawater primarily driven by tidal forces, play a fundamental role in shaping marine ecosystems (Nathaniel, 2002). Accurate monitoring of tidal currents is essential, as these dynamics significantly influence the transport of nutrients, distribution of aquatic organisms, and various chemical and physical processes within coastal waters (Eggertsen *et al*., 2016). Traditionally, current measurements have relied on Acoustic Doppler Current Profilers (ADCP), which provide detailed vertical profiles of water velocity (Ribotti *et al*., 2019). However, ADCP systems are often costly to deploy and maintain, limiting their accessibility for long-term or widespread monitoring in developing regions (Respati *et al*., 2020). As an alternative, drifting buoys have emerged as a practical and cost-effective solution for collecting surface current data.

Sea surface temperature is another critical oceanographic parameter, governing air-sea interactions, influencing mesoscale oceanic variability, and serving as a key variable in climate modeling and forecasting (Elipot *et al*., 2022; Oussama, 2020). Reliable SST monitoring is therefore crucial for both scientific research and environmental management (Rifai *et al*., 2020). While advances in remote sensing have enabled SST estimation from satellite imagery (Jang and Park, 2019), these methods face significant limitations in complex coastal environments, particularly in lagoons with intricate networks of narrow channels. Satellite sensors often lack the spatial resolution required to capture fine-scale thermal gradients in such confined waterways, while cloud cover, atmospheric aerosols, and land adjacency effects further degrade data quality. Buoy equipped with high-resolution temperature sensors can capture real-time, localized SST variations even in tight channels where remote

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sensing falls short (Castro *et al*., 2012). Moreover, such platforms serve as essential reference points for calibrating and verifying satellite-based observations (Knedy, 2013).

Segara Anakan Lagoon comprises a complex tidal channel network connecting it to the Indian Ocean, with the Donan River as the main outlet. This estuary exhibits tidal asymmetry dominated by flood current (Khadami *et al*., 2020). Seasonal monsoon rainfall notably affects water flow by increasing river discharge and influencing ecosystem dynamics (Pratiwi and Sukardjo, 2018). Although coastal organisms generally tolerate a wide temperature range, temperature critically impacts lagoon ecosystems, affecting metabolic rates, reproduction, and species distribution (Giordano *et al*., 2012). Shallow depths and limited water exchange in Segara Anakan predispose it to temperature fluctuations that may exceed optimal conditions for many species. Temperature also integrates multiple environmental stressors, correlating with salinity, dissolved oxygen, and pH levels, thus serving as a proxy for ecosystem health (Haddout *et al*., 2022).

Ocean currents and SST are pivotal in understanding the physical, chemical, and biological dynamics of coastal environments (Eggertsen *et al*., 2016; Rifai *et al*., 2020; Schmiing *et al*., 2013). The survey technique using buoy is closely related to marine instrumentation because many sensors are used to collect marine data. One of the technologies used is the drifting buoy. The use of drifting buoy has been around since (1452 - 1519) by Leonardo da Vinci to measure water speed in rivers (Unesco, 2016). The development of the era has made the drifting buoy a very useful instrument for monitoring the hydrodynamics of water (Martínez-ledesma, 2018). Previous studies have examined drifting buoys for sea surface temperature monitoring, revealing sensor biases and temperature-dependent offsets in common SST thermistors (Reverdin *et al*., 2010). Advances include the development of a new buoy equipped with high-resolution sensors calibrated to international standards, ensuring precise and reliable temperature data (Le Menn *et al*., 2019). Additionally, educational initiatives have created low-cost, Arduino-based drifters that provide real-time environmental data to support local aquaculture (Eaton *et al*., 2025). The purpose of this study was to design a smart buoy drifting tool that can provide data on monitoring the dynamics of waters in Segara Anakan Lagoon.

MATERIALS AND METHODS

The research was divided into five stages: design, manufacturing of the drifting buoy, tool testing, field data collection, and data analysis. The design stage included two main aspects: Electronic Design and Physical Design. The Electronic Design focused on creating a GPS tracking system and temperature sensor using an ESP32 microcontroller. Data obtained from the sensors are stored on an SD Card for recording purposes and simultaneously transferred to a laptop via radio communication using a LoRa receiver. The Physical Design involved the buoy's shape and structure, with the upper part made into a circle wider than the buoy's body to maintain buoyancy in the water. The overall height of the buoy cover is 50 cm, enabling its use in narrow waters with shallow depths.

Electronic Design

The electronic devices consist of the transmitter device installed on the buoy (Figure 1a) and the receiver device (Figure 1b). The transmitter uses an ESP32 microcontroller as the Central Control Unit (CCU) connected to a LoRa E32 433T20D module as the telemetry device, a Neo-M8M GPS sensor for geographic positioning, a DS18B20 temperature sensor for measuring water temperature, a MicroSD module for local data storage, and a power source consisting of a 3.7 VDC battery. Meanwhile, the receiver consists of an ESP32 microcontroller connected to the same type of LoRa module to receive data transmitted by the transmitter.

Physical Design

The physical form of the drifting buoy consists of a floatation part and a current-catching part submerged in the water. This current-catching part is called a drogue. Figure 2a-2c present the technical schematics of the drifting buoy with detailed dimensions. The floatation section is designed as a flat circular structure with a diameter of 40 cm and a thickness of 8 cm. A cylindrical ballast, serving also as battery housing, is attached below the floatation section, with a diameter of 7.62 cm (3 inches) and a height of 21 cm. The flat profile of the floatation section minimizes exposure above the water surface, thereby reducing wind-induced drag and improving drift accuracy.

The drogue element, which provides hydrodynamic resistance, is a cylindrical structure with a diameter of 30 cm and a height of 50 cm. Its dimensions were tailored to the hydrological conditions of the research site. Given that the study was conducted in a shallow lagoon, the drogue was intentionally designed to be of moderate length to prevent contact with the seabed and avoid entanglement during deployment.

Figure **2**d shows a photograph of the deployed drifting buoy floating on the water surface, featuring a predominantly orange color to enhance visibility during field observation.

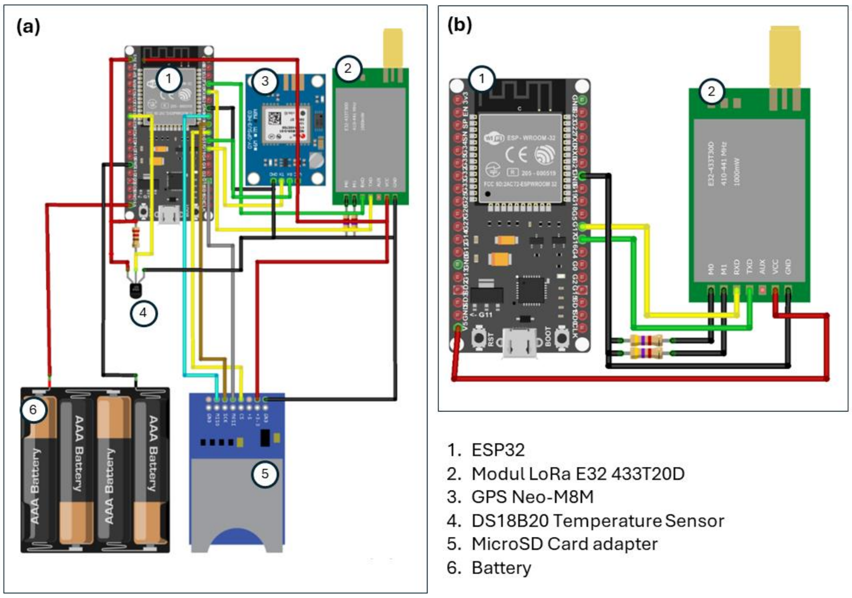

Figure 1. Electronic Schematics of the Drifting Buoy System: (a) Transmitter unit installed on the drifting buoy, illustrating the wiring and components; (b) Receiver unit schematic showing ESP32 microcontroller and LoRa module for wireless data reception.

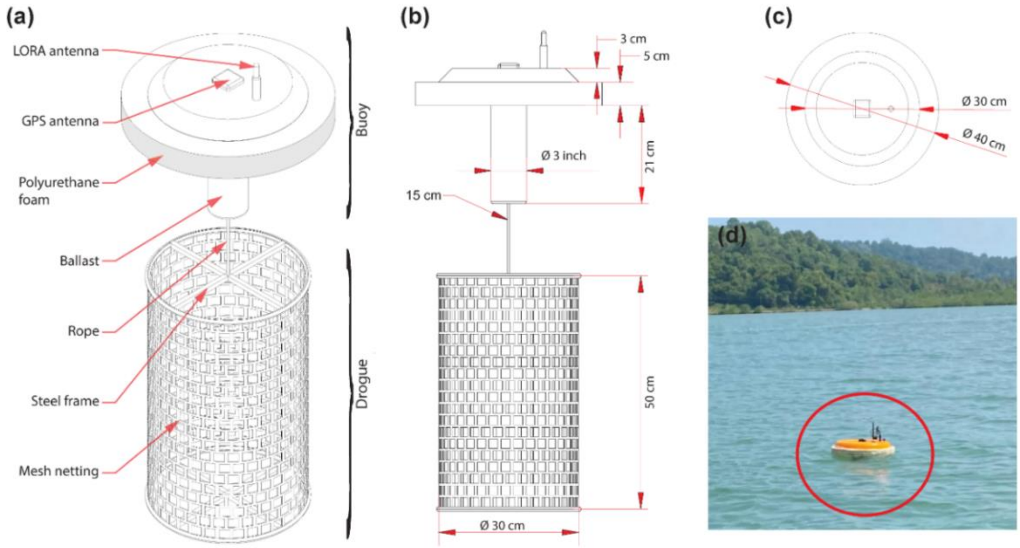

Figure 2.Physical design and implementation of the drifting buoy, (a) exploded view illustrating the main components, (b) side view with detailed dimensions, (c) top view showing the diameters, and (d) actual photograph of the drifting buoy floating during field deployment.

Tool Trial Procedures

The tool trial activity was conducted in the experiment pond of the Faculty of Fisheries and Marine Sciences, Jenderal Soedirman University, which remained floating for 3 days. GPS Sensor testing was performed by recording data at one point for 5 minutes in three conditions namely in an open field, near a building, and under shady tree. The recorded data was analyzed to determine how much error occurred and converted into distance. After that, the sensor was tested for tracking, and the results were analyzed to see the path pattern produced by the GPS Neo-M8N. Testing of the DS18B20 temperature sensor was conducted by measuring the temperature of warm water that was left until the temperature dropped. Temperature measurements from the sensor were compared with those obtained using a standard calibrated thermometer to validate sensor accuracy. The results are presented in terms of the DS18B20 sensor's measurement accuracy relative to the reference thermometer.

Additionally, a scenario was included to simulate the condition in which the buoy stops moving due to grounding in shallow bathymetry. In this scenario, the buoy was monitored to observe its behavior and data recording continuity while stationary in shallow water. Procedures for handling this situation involved recording any positional drift or signal loss and restarting or relocating the buoy if necessary to resume data collection. This approach aims to reflect realistic challenges in lagoon environments such as Segara Anakan Lagoon, ensuring the robustness of the monitoring system under varying shallow water conditions.

Field Data Collection

Field observations were conducted in May 2024 in the waters of Plawangan Timur, Segara Anakan, Cilacap, Central Java, a dynamic coastal lagoon system influenced by the convergence of riverine freshwater and seawater from the Indian Ocean. The estuarine main channel width ranges from 300 to 600 meters within the estuarine zone and narrows to less than 300 meters in the central lagoon. Bathymetric surveys indicate channel depths between 2 and 5 meters centrally, increasing to 8 to 16 meters near the ocean entrance. These hydrodynamic and morphometric characteristics provide the physical context underlying the observed temperature variability and ecological sensitivity of the lagoon environment. The study site, identified as the tidal flow convergence point, is where the buoy was deployed (Figure 3).

The results of the field data recording are still in the form of longitude and latitude, then converted into direction and speed values. The current velocity and direction can be obtained from the following Haversin Formula (Pitman *et al*., 2020) and velocity calculation with equation: 1-3.

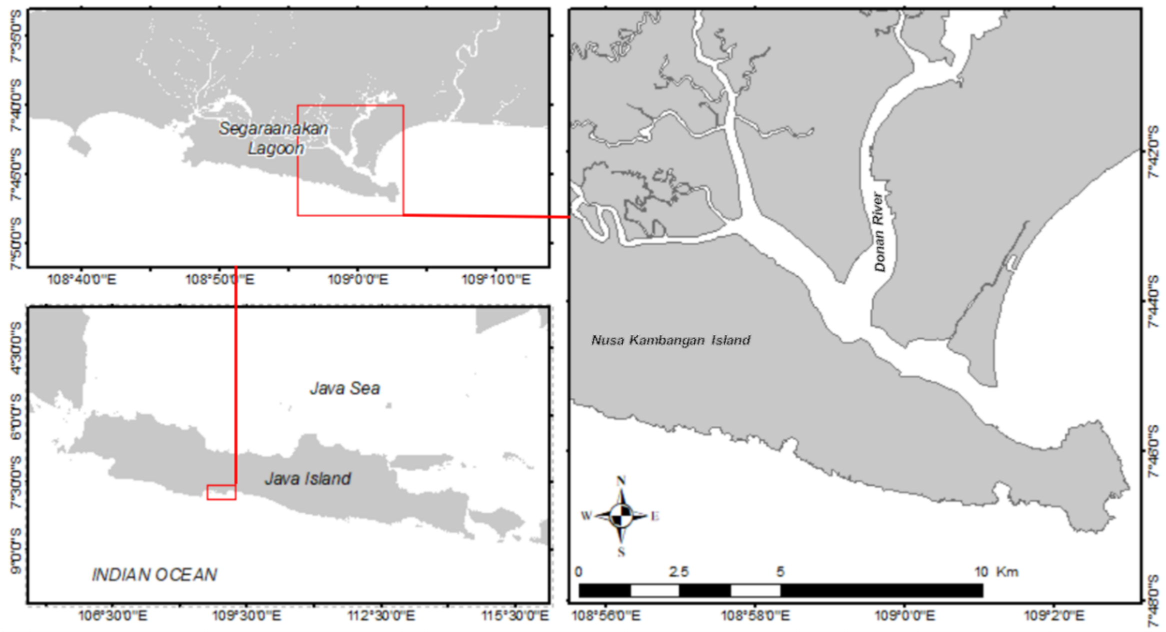

Figure 3. Map of the study area

$$D = 2r\sin^{-1}\left(\sqrt{\sin^2\left(\frac{Y2-Y1}{2}\right)+\cos(Y1)\times\cos(Y2)\times\sin^2\left(\frac{X2-X1}{2}\right)}\right) \ldots (1)$$

$$V = \frac{D}{t} \ldots (2)$$

$$a = \left(\sin^2\left(\frac{\Delta Y}{2}\right)+\cos Y1\times\cos Y2\times\sin^2\left(\frac{\Delta X}{2}\right)\right)\times 0{,}0174532925 \ldots (3)$$

Note: D = distance (meter); Y = latitude; X = longitude; r = average radius; V = velocity (m/s); t = time of point transfer (s); a = direction (radians)

RESULT AND DISCUSSION

GPS Accuracy Evaluation

The Neo-M8N GPS test produced different error values in each condition (Figure 4) (Gunathilaka *et al*., 2023). The results showed that in open field GPS conditions, the farthest error value recorded was 2.3 meters, with the number of points with a value of more than 2 meters at 13.9%. The results of the GPS conditions placed next to the building showed the farthest error of 3.1 meters with a number of points of 4.8%. The farthest error in conditions near trees showed a value of 3.7 meters with a number of points of 14.3%. The largest error in open field conditions was due to slightly disrupted communication between GPS and satellite (Fakhrulddin *et al*., 2020). GPS and satellite communication are disrupted due to obstacles from buildings that reflect electromagnetic signals (Al-Hraishawi *et al*., 2023). The error in the tree area was greater than the previous two conditions because satellite communication was blocked by trees (Qiu *et al*., 2020).

Validation of Temperature Sensor

The calibration process of the DS18B20 temperature sensor (Figure 5) was conducted by measuring the temperature of warm water that slowly cooled down using a thermometer as a standard measuring instrument and the assembled DS18B20 temperature sensor. The results of the calibration obtained a standard error value of 0.37. The regression results between the thermometer and the DS18B20 showed an R^2 value of 0.9989, which means that the regression model built has a very good level of fit (Koestoer *et al*., 2019). The results of this trial prove that the DS18B20 sensor used is very reliable and has high precision.

Field Measurement of Current Dynamics

The movement of the tide flowing toward the coast, including into bays and estuaries, is known as the flood current, while the flow heading back out to sea is called the ebb current. These currents tend to be strongest shortly before the time of high and low tides. The period of minimal current that occurs between the flood and ebb phases is referred to as slack tide. In the open ocean, tidal currents are generally weak; however, near estuary mouths, narrow straits, and inlets, they can reach speeds of several kilometers per hour. The tidal type in Segara Anakan Lagoon was mixed tide prevailing semi-diurnal (Holtermann *et al*., 2009). Data collection was carried out when the waters were positioned for flood current at 10:30 a.m. until they were positioned for ebb current at 14:46 p.m. The buoy tracking showed that during high tide conditions, the current entered as far as 6.5 km and returned to the sea during low tide. The tidal data used in this study are results of a model based on in situ measurements at the monitoring station of the Cilacap Navigation District (coordinates: 7.725110° S, 108.997126° E). Tidal currents are influenced by the existing tidal phenomena (Wiyadi *et al*., 2022). The current speed during high tide had a higher value than during low tide. The speed value during high tide ranged from 0.052 - 0.78 m/s, then the current weakened during low tide (Figure 6). This is in accordance with the research of Yuniarti *et al*. (2018) which stated that the current in the Eastern Segara Anakan Waters had a value between 0.1 - 0.76 m/s. The conditions during low tide have a smaller value due to the influence of the opposite wind. The wind power that influences surface currents is around 2% of the wind water speed itself (Sari *et al*., 2020).

During the period between 10:00 a.m. and 11:55 a.m. (WIB), the current velocity reached its peak. This condition indicates that the waters were in the phase of approaching high tide (Figure 6). In general, tidal currents tend to reach their maximum velocity during transitional phases, specifically when the water is moving toward the lowest ebb (low tide) or the highest flood (high tide), as significant differences in sea surface elevation drive the movement of large volumes of water (Waru, 2022). According to (Hermansyah *et al*., 2020), tidal currents are strongly influenced by lunar phases, seabed topography, and coastal geometry, all of which can modify both the speed and direction of the current. Moreover, the increasing current during the rising tide phase plays an important role in distributing nutrients and affecting the salinity and temperature of the waters.

The results of data collection also obtained the sea surface temperature values in these waters. The temperature values obtained ranged from 28.31-29.37°C (Figure 7). Temperature recording is greatly influenced by the time of data collection. Sea Surface Temperature is influenced by sunlight (Kusuma *et al*., 2023). The temperature values of the eastern Segara Anakan waters range from 28.1 -28.7 ° C (Priska *et al*., 2020). The sea surface temperature values indicate that the waters are in good condition. Waters with good conditions have water temperature values between 28-30°C (Dwiyanti *et al*., 2023)

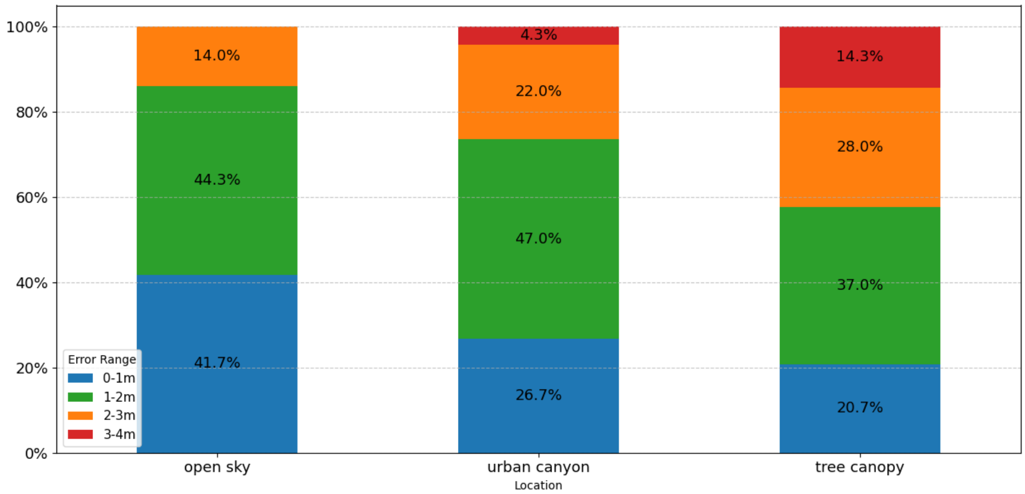

Figure 4. Number of Neo-M8N GPS Accuracy Test Recording Points

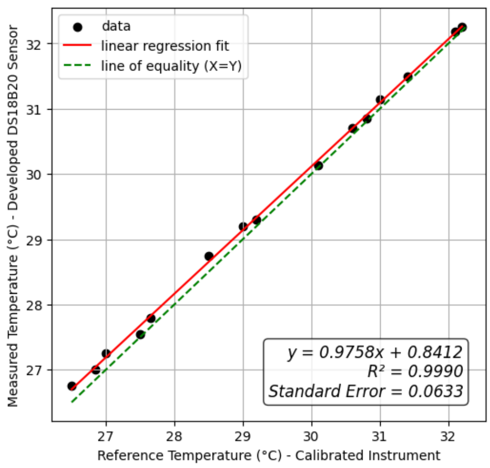

Figure 5. Regression between DS18B20 temperature sensor and standard thermometer

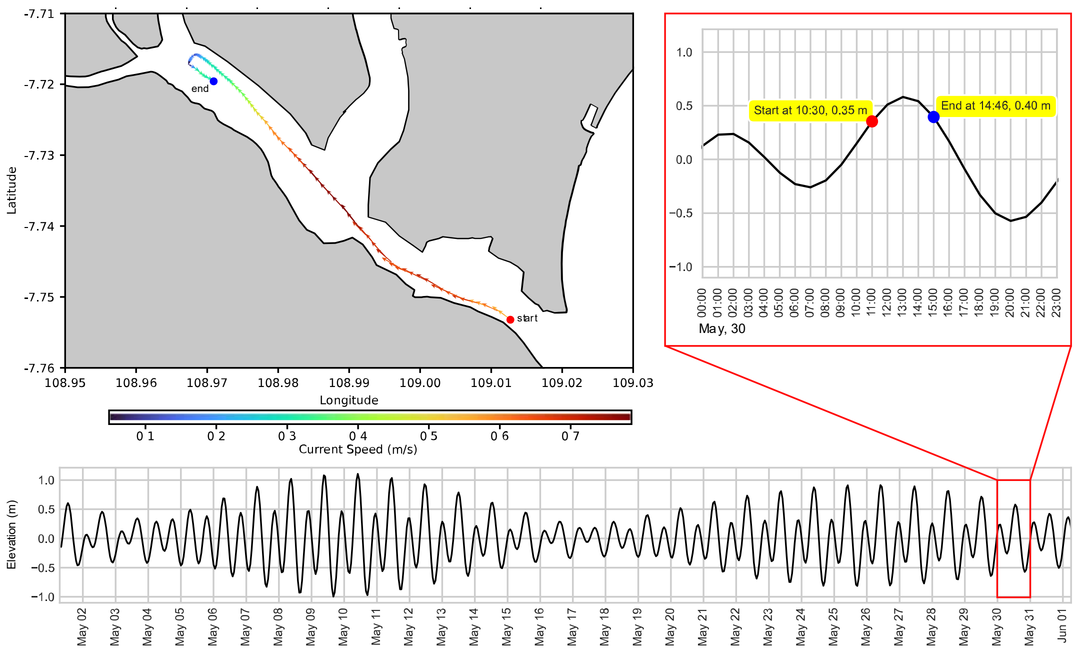

Figure 6. Trajectory and Current Speed Variations under Tidal Influence using Drifting Buoy

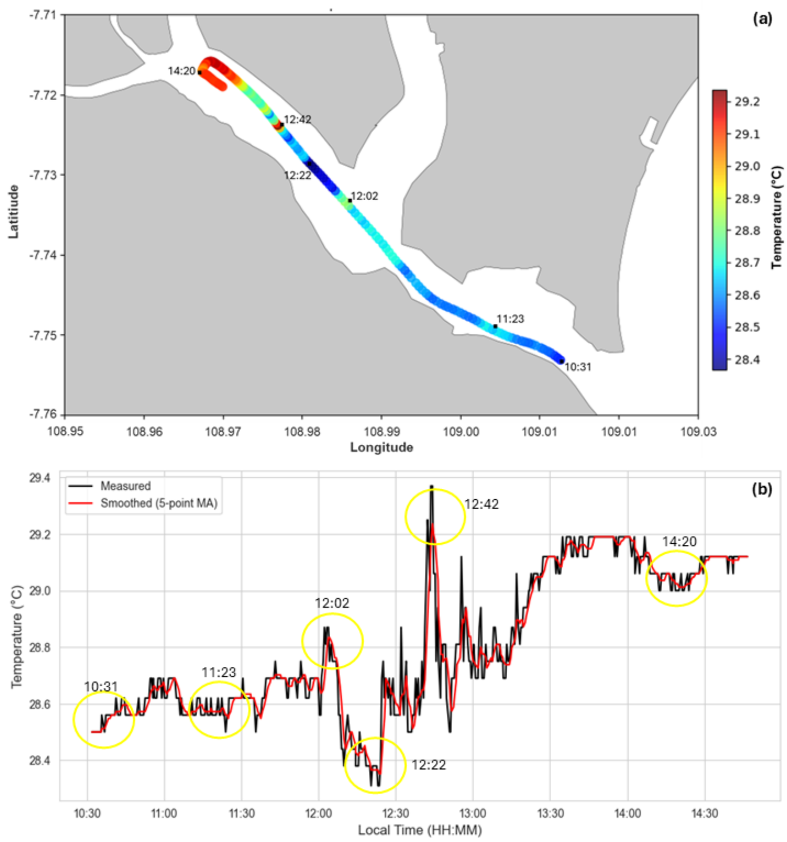

Figure 7. Temperature variation along the drifting buoy trajectory in Segara Anakan Eastern Waters. (a) Spatial distribution of water temperature (°C) measured along the buoy's path, with time stamps marking key points. (b) Temporal temperature changes during the measurement period, showing raw data (black line) and smoothed values using a 5-point moving average (red line).

The graph shows that the temperature decreased from 11:45 a.m. to 12:20 p.m. and then increased from 12:36 p.m. The condition of the decrease in temperature was caused by the surrounding weather which was covered by clouds. Air humidity, clouds, and other atmospheric activities are additional components that affect daily temperature changes (Suhanda and Putra, 2021). The presence of clouds can reduce the amount of solar radiation reaching the sea surface, thereby reducing the increase in temperature during the day (Panjaitan *et al*., 2021). Due to the intense solar radiation during the day, especially in tropical and subtropical areas, heat from the sun is absorbed by the surface layer of the sea, causing the temperature to rise (Huang *et al*., 2021). The drifting buoy was at the confluence of the river and the sea during that time, which may have also contributed to the decrease in temperature. The mixing process of these two types of water, supported by currents that carry cold water from the river to the sea, as well as lower evaporation rates in the confluence zone, results in a significant decrease in temperature compared to the surrounding sea water temperature (Oktafianda and Suriani, 2024).

CONCLUSION

The deployment of a drifting buoy in Segara Anakan Lagoon has proven effective in tracking ocean currents and sea surface temperature (SST) in real time. The GPS sensor demonstrated high accuracy, with a positional error of 1–2 meters across varied environmental conditions, while the temperature sensor showed excellent agreement with reference measurements (R^2 = 0.9989). Observations revealed current speeds ranging from 0.052 to 0.78 m/s, with distinct tidal influence, flowing into the river mouth during high tide and seaward during low tide. Sea surface temperatures varied between 28.5 °C and 29.37 °C, reflecting dynamic thermal conditions in the lagoon. This study underscores the potential of drifting buoys as reliable tools for continuous oceanographic monitoring in complex coastal environments.

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