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Evaluating Mooring Designs for ADCP Data Quality in the Strong Kuroshio Current: A Comparative Study of Elliptical Buoys and Stablemoor Buoys

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ABSTRACT

This study presents a comprehensive analysis of data quality from Acoustic Doppler Current Profiler (ADCP) observations in the strong Kuroshio current off southeastern Taiwan, comparing two mooring designs: the "Elliptical ADCP Buoy" (EAB) and "StableMoor Mooring Buoy" (SMB). The Kuroshio current is critical for understanding regional ocean dynamics, climate variability, and marine ecosystems. Accurate ADCP measurements are vital for capturing the current's velocity structure, and data quality can be significantly impacted by the mooring configuration. During a two-year field experiment, the EAB was deployed during the first phase (2022-2023) and the SMB in the second phase (2023-2024). This study compares the data collected from both mooring buoy types, with a focus on the impacts of ADCP motion and orientation on data quality. The SMB, deployed for the first time in Taiwan, successfully conducted year-long measurements in the Kuroshio current, providing recommendations for mooring designs for challenging environments.

The results indicate that the SMB generally produces lower noise levels and more consistent velocity profiles. The SMB's design, which reduces form drag and resists mooring deflection, contributes to more stable observations. In contract, the EAB offers broader spatial coverage due to it being knocked down by ocean currents, and it exhibits data coverage variability. This variability is likely attributed to the deflection of the mooring system, which can introduce biases in the ADCP measurements. These findings highlight the impact of buoy shape on mooring design for in-situ ADCP observations. The insights gained from this analysis can contribute to improving observational strategies for ocean current monitoring in complex and dynamic marine environments. With the higher data quality associated with the SMB, researchers can make informed decisions on mooring configurations that best suit their observational goals.

Keywords: mooring observation, StableMoor mooring buoy, Elliptical ADCP buoy, Kuroshio current.

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1 INTRODUCTION

The Kuroshio current, one of the strongest western boundary currents in the world, flows northward along the east coast of Taiwan. It significantly impacts ocean dynamics, climate systems, material transport, and ecological environments. Since the early 20th century, observing the Kuroshio current has been a key focus in oceanographic and meteorological research, particularly in the context of climate change. Understanding the variations of the Kuroshio current is crucial for understanding regional and global climate systems. To gain an in-depth understanding of the structure and variability of the Kuroshio current, researchers have employed various observation techniques to collect oceanic data. Tseng et al. (2011) used satellite-derived sea surface temperature (SST) and Argos satellite-tracking Lagrangian drifters to study the variations of the Kuroshio current. Their findings show that the current speed and temperature fluctuations in the Kuroshio current vary significantly with the seasons, particularly affecting the marine environment in eastern Taiwan. Chen et al. (2015) utilized Argo data to investigate the seasonal and ENSO-related interannual variability of subsurface fronts separating the West Philippine Sea waters from South China Sea waters near the Luzon Strait. Their study highlighted the importance of these subsurface fronts in modulating the water mass mixing processes and their broader ecological impacts in the region, offering critical insights into the dynamic interactions between the Kuroshio current and surrounding waters.

Among the many tools used to measure the Kuroshio's structure and variability, Acoustic Doppler Current Profilers (ADCPs) are commonly used to measure current velocity profiles. Johns et al. (2001) utilized ADCPs to obtain deep-water current speed data of the Kuroshio current, demonstrating that the current speed gradually weakens with depth in the deep-sea region east of Taiwan, and even exhibits reverse flow at certain depths, providing valuable information for understanding the three-dimensional structure of the Kuroshio current. Lien et al. (2014) conducted an in-depth study of the Kuroshio's structure and variability in the waters east of Taiwan by using mooring observation. The study found that the current speed of the Kuroshio current significantly decreases with increasing depth in its vertical structure, and mooring data also revealed the seasonal variations influenced by monsoons. Through the application of various advanced technologies, from the macroscopic understanding provided by satellite remote sensing to the complementary monitoring methods of moored ADCPs, shipboard ADCPs, Argo data, and seabed observation stations, researchers have been able to comprehensively understand the dynamic changes of the Kuroshio current and its impact. These observation methods and research findings not only enhance our understanding of the Kuroshio current but also provide important scientific evidence for climate change research and marine environmental protection.

From 2012 to 2015, the OKTV project (Observation of the Kuroshio Transports and their Variability) conducted extensive in-situ observations of the Kuroshio's structure. Three transects were mainly established across the east-west axis of the Kuroshio current, which were repeatedly surveyed by the R/Vs *Ocean Researcher I, III,* and *V* (e.g., *OR1*, *OR3*, and *OR5*). These research vessels conducted 18 cruise missions in total to measure the velocity profiles in upper 600 m along KTV1 (~23.75ºN), KTV2 (22.75ºN), and KTV3 (22ºN) by using a 75 kHz shipboard ADCP (sbADCP) equipped on each of them. Yang et al. (2015a, b) further pointed out, based on the average results from shipboard observations under the OKTV project, that the Kuroshio velocity and hydrographic structure exhibit a dual-core phenomenon. The dual core structure of the Kuroshio current was partly concluded from sbADCP observation during cruises. The coverage of the sbADCP is only about 200 m of topmost layer. The variation of dual core structure is still not well understood. Therefore, it is important to conduct a long-term field experiment to observe the Kuroshio current in this region.

Mooring observation is an effective method for monitoring the Kuroshio current, and it especially suitable for long-term observation of its core areas. Off eastern Taiwan, researchers have used mooring observations to deploy instruments at specific locations along the mainstream of the Kuroshio current. These instruments

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typically include ADCPs, CTDs (conductivity-temperature-depth), and other oceanic sensors. Through mooring observations, researchers can obtain continuous data on the current speed, temperature, and salinity changes in the Kuroshio current, providing essential insights into the dynamic structure, variability, and long-term behavior of this powerful ocean current. As shown by the research on the Tokara Strait of Feng et al. (2000), mooring observations are invaluable in capturing the Kuroshio's complex structure and seasonal variability, which are influenced by interactions with regional topography and changing oceanic conditions. Their study found that the Kuroshio current exhibits significant fluctuations in current speed and depth structure as it flows through constricted regions like the Tokara Strait, highlighting the importance of continuous, high-resolution observations to fully understand these dynamics. However, the strong Kuroshio current could knock down the mooring system and often challenges its stability. In addition, mooring deflection could influence data quality and the coverage range of ADCP measurements. These findings underscore the importance of implementing data correction methods to maintain measurement reliability in high-velocity current environments. Lerczak and Geyer (2004) mentioned the effects of strong currents and lateral flows on ADCP measurements. The literature review further confirms the impact of strong currents on mooring systems and data quality, but these effects can be effectively mitigated by optimizing buoy shape and data processing methods. Ma et al. (2022) explored the structure and variability of the Kuroshio current and Luzon Undercurrent (LUC) using mooring array observations. Their findings focused on the variability of the Kuroshio current and its interaction with the LUC, particularly in dynamic ocean regions with strong currents, such as those near Taiwan. This study underscores the importance of enhancing buoy and mooring system designs to ensure accurate data collection in challenging environments. Scannell et al. (2022) found that due to mooring design limitations, ADCPs can experience motion-induced biases that significantly impact data accuracy, especially in high-current areas. For instance, in strong currents, ADCPs may oscillate or tilt, leading to measurement biases that can reach up to 10-30% under certain conditions. These biases primarily affect the precision of high-frequency, small-scale turbulent processes. Improving mooring stability in these dynamic regions is thus crucial for obtaining reliable observations of Kuroshio's long-term behavior and broader climate impact. Andres et al. (2008) and Lien et al. (2014) studied the hydrodynamic characteristics of Kuroshio variability and examined the performance of mooring systems under extreme climatic conditions, proposing recommendations to enhance the stability of observation equipment.

With technological advances, the design of buoys has become crucial in reducing sway and tilt in strong current environments. The shape and hydrodynamic properties of buoys play a significant role in improving stability by reducing drag, which is essential for reliable data collection. For example, Harding et al. (2017) demonstrated how compliant moorings can minimize motion in turbulent environments, thus improving the accuracy of measurements. Similarly, Nicoll (2019) emphasized the importance of controlling uncertainty in buoy drag coefficients, particularly in the design phase of oceanographic moorings. By optimizing the hydrodynamic design of buoys, such as adopting flatter, streamlined shapes, it is possible to reduce fluid resistance, thereby minimizing the risk of sway and tilt. Horwitz and Hay (2017) further explored how turbulence dissipation rates can be measured more accurately when horizontal velocity profiles remain stable, underscoring the need for reliable mooring systems in dynamic ocean conditions. These studies highlight the critical role of buoy design in enhancing stability and data reliability, especially for long-term ocean observations in strong current environments.

As previously mentioned, the Kuroshio current exhibits significant fluctuations and possesses powerful speeds, making it difficult to observe. Therefore, each observation attempts to maximize spatial and temporal coverage as much as possible. This study analyzes the data quality of the first-time use in Taiwan of a "StableMoor Mooring Buoy" (SMB) in Kuroshio observations and compares it with an "Elliptical ADCP Buoy" (EAB) in Figure 1, further examining the differences in data quality between the two mooring designs.

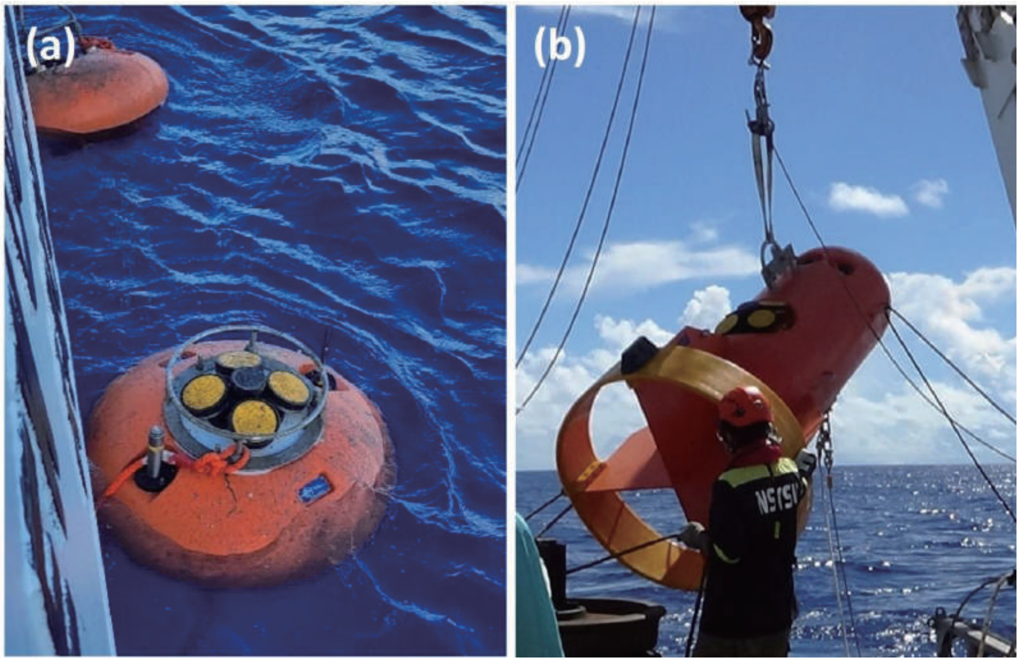

Figure 1. (a) Elliptical ADCP Buoy (EAB) and (b) StableMoor Mooring Buoy (SMB). The EAB equipped with a 100 kHz ADCP was retrieved by R/V *NOR3* on July 20, 2023, while the SMB, also equipped with a 100 kHz ADCP, was deployed by R/V *NOR3* on July 7, 2024.

2 FIELD EXPERIMENT

2.1 Location and Mooring Design

To observe the annual variability of the Kuroshio current off the southeastern coast of Taiwan, a strategic deployment of two mooring systems was implemented between the southern tip of Taiwan and Lanyu Island (also known as Orchid Island), approximately 20 km east of Nanwan Bay. As illustrated in Figure 2, this location can observe the variations in the Kuroshio current field as well as the internal waves generated in the Luzon Strait. The water depth at this site averages around 1,000 m, providing a suitable environment for the two-year field experiment that spanned from 2022 to 2024. The two moorings installed at this location included one Acoustic Doppler Current Profiler string (ADCP-string) and one thermometer string. However, for the purposes of this study, the focus will be on the ADCP-string, which was the primary tool for measuring the time series of vertical ocean currents profile. The ADCP-string plays a crucial role in understanding the dynamics of the Kuroshio current, which is one of the strongest western boundary currents in the world and significantly influences the climate and marine ecosystem in the region.

In the initial deployment (phase 1, 2022-2023), as shown in Figure 3a, the ADCP-string was equipped with two Nortek ADCPs. The first ADCP, an upward-looking Nortek 100 kHz model, was positioned at a depth of 390 m. This configuration allows the ADCP to measure current velocities in the water column above it, extending from the deployment depth to near the surface. The second ADCP, a downward-looking Nortek 55 kHz model, was positioned at a depth of 400 m, aimed at capturing data from the water column below it. Both ADCPs were installed in "Elliptical ADCP Buoys" (EABs). The deployment of these moorings was carried out by the R/V *New Ocean Researcher 1* (*NOR1*) during its 36th cruise expedition from July 6-11, 2022. The precise locations of the moorings were determined using the triangulation method, with the ADCP-string deployed at coordinates 21.9°N and 120.97°E. This careful placement ensured that the instruments would be optimally positioned to monitor the Kuroshio current over the course of the following year.

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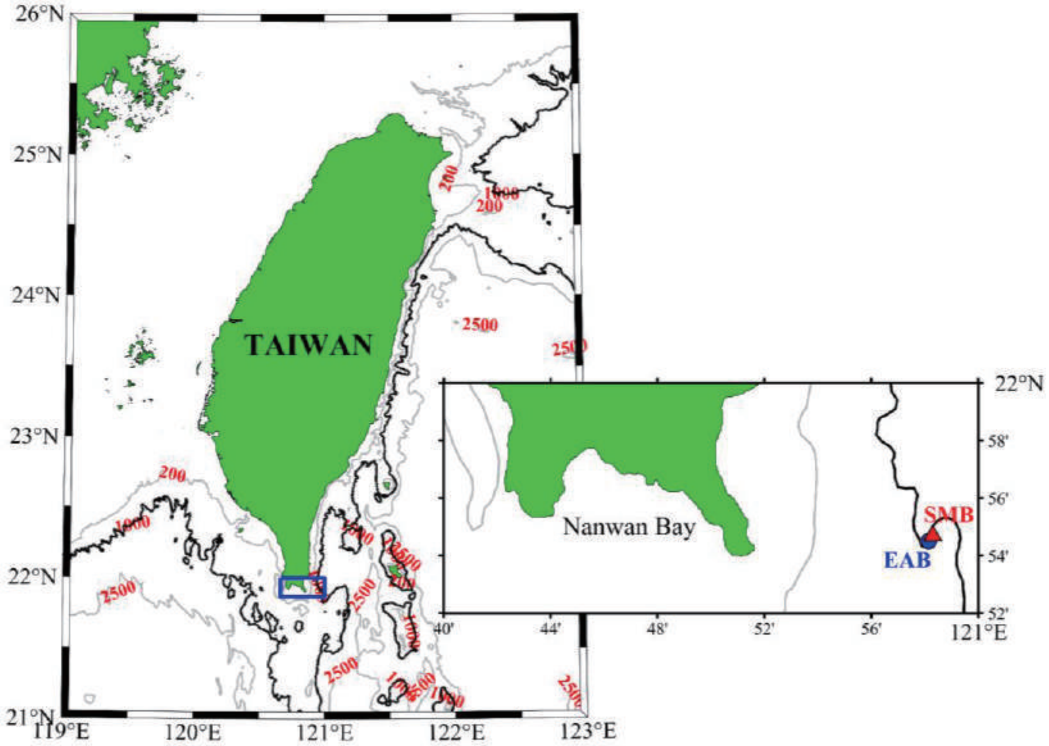

Figure 2. Location of moorings in the field experiment of 2022 (phase 1; EAB) and 2023 (phase 2; SMB).

After one year of data collection, the retrieval of the ADCP-string was undertaken by the R/V *New Ocean Researcher 3* (*NOR3*) during its 167th cruise expedition, which took place from July 18-22, 2023. During this mission, the moorings were successfully recovered, and a new set of moorings, incorporating updated designs, was deployed to continue the hydrographic survey for another 12 months (phase 2, 2023-2024). This new deployment, shown in Figure 3b, included several modifications aimed at enhancing the stability and performance of the ADCP-string. One of the key upgrades in the new deployment was the introduction of a "StableMoor Mooring Buoy" (SMB) to protect the upward-looking Nortek 100 kHz ADCP. This ADCP was placed at a slightly shallower depth of 380 m. The SMB is specifically designed to provide superior stability in the water column to reduce vertical motion. In our mooring design deployed in the Kuroshio region, a stainless-steel mooring swivel was installed beneath the SMB and allowed for smooth transitions from changes in current direction. This design works particularly well with the torpedo-shaped SMB, allowing it to effectively resist currents while collecting data stably. In the July 2023 experiment, the SMB provided a net buoyancy of 396 kg, approximately 250 kg more than the 143 kg buoyancy of the EAB, requiring the use of more train wheels to secure the system to the seabed. The increased net buoyancy also helped align the anchor chain more vertically in the water. The downward-looking Nortek 55 kHz ADCP remained at the same depth of 400 m, still mounted on an EAB. This combination of a stable moor for the upper ADCP and an elliptical moor for the lower one represents an innovative approach to maintaining the integrity of the data collected in such a dynamic environment. This ADCP-string was then successfully retrieved by the *NOR3* again during its 223rd cruise expedition, which took place from July 6-9, 2024.

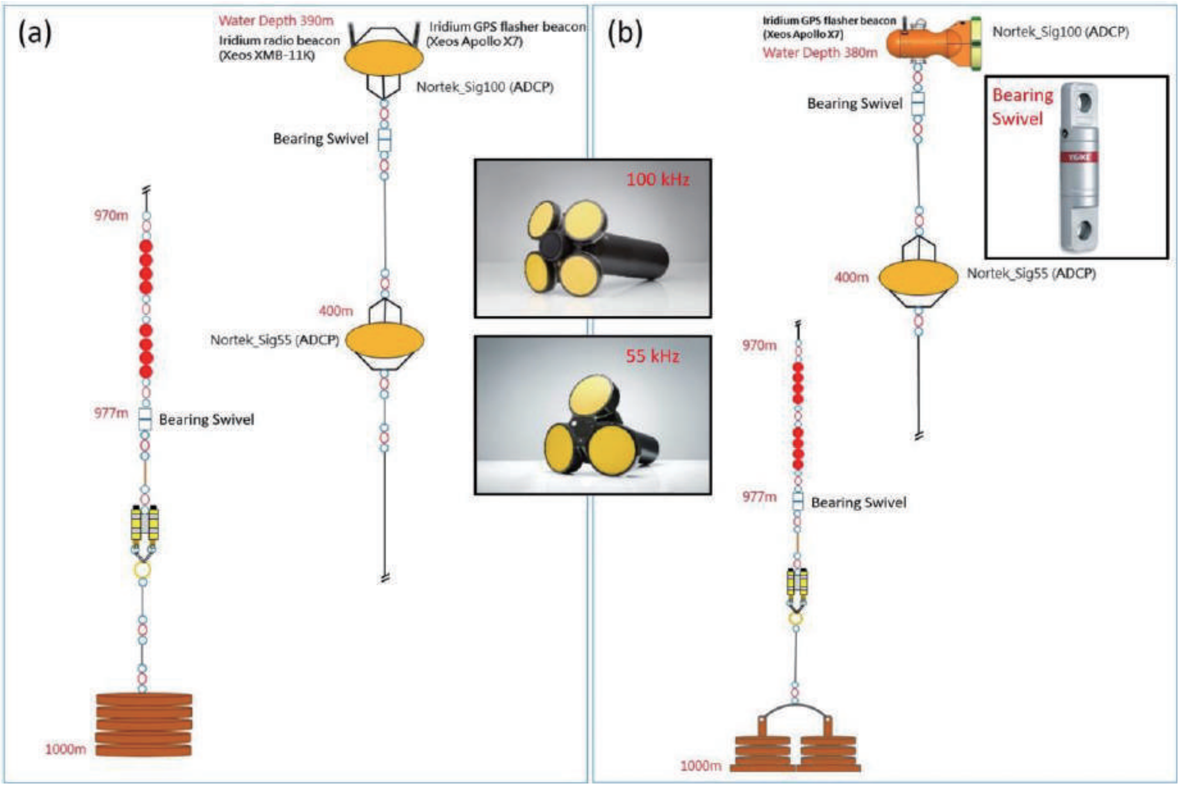

Figure 3. Schematic diagrams of ADCP moorings during (a) phase 1 (2022-2023) and (b) phase 2 (2023-2024) of the two-year field experiment off southeastern Taiwan.

2.2 Moor Types and Data

This study utilizes two types of mooring systems developed by DeepWater Buoyancy Inc.: the "Elliptical ADCP Buoy" (EAB) and the "StableMoor Mooring Buoy" (SMB). Both mooring systems were deployed at different times, each mounted with a Nortek Signature 100 kHz ADCP, to observe the Kuroshio current off the southeastern coast of Taiwan. The study focuses on assessing the performance of these mooring systems in the strong Kuroshio current, particularly examining the differences in current speed, data quality, and the stability of the equipment's orientation underwater.

The EAB is designed with a 1.15 m diameter of elliptical shape and manufactured from DeepTec® syntactic foam for measuring current velocity. Its hydrodynamic design aims to reduce sway and tilt in strong currents, ensuring more stable data collection. Compared to spherical buoys, the ellipsoidal buoys have a better streamlining to eliminate vortex shedding and to reduce shaking of the buoy. On the other hand, the SMB is designed with 0.75 meters in diameter and 2.48 meters in length and made from DeepTec® syntactic foam with a high-strength GRP tail. It features a protective glass-reinforced plastic shell, an elongating torpedo-shaped body, and a cross-vane tail to reduce form drag and increase its dynamic stability. For a SMB with the same buoyancy as a spherical buoy, the drag area is a factor of 2.5 smaller (Ryan, 2023). This design makes the SMB suitable for long-term mooring observations in extreme and challenging flow conditions. The study highlights the SMB's ability to provide reliable data, even in regions with strong currents. Harding and Kilcher. (2017) demonstrated that the SMB maintained high stability during midwater turbulence measurements, reducing buoy tilt even when currents exceeded 1.0 m s^{-1}, ensuring accurate data collection. Similarly, McVey and Kilcher (2021) indicated the SMB's effectiveness in tidal energy studies in Alaska's Cook Inlet, where it maintained stability in turbulent conditions. These findings confirm the SMB's suitability for challenging environments such as the Kuroshio current, Gulf Stream, and Antarctica.

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A comprehensive analysis was performed on time-series data collected from two Nortek Signature 100 kHz ADCPs mounted on the EAB and SMB, including measurements of depth, pitch, roll, heading, velocity, and percentage good (PG). Both ADCPs recorded data at 10-minute intervals. The ADCP on the EAB used an 8-meter bin size, while the ADCP on the SMB set a 10-meter bin size.

3 RESULTS AND DISCUSSION

In this study, two different mooring designs of EAB and SMB, were employed to assess their performance in observing current velocity in the Kuroshio current off southeastern Taiwan. Comparing these two mooring systems in a region influenced by strong currents, particularly the Kuroshio current and internal waves, provides valuable insights into their effectiveness under challenging oceanographic conditions. The study focuses on how these two buoys respond to strong and highly variable velocity conditions, and how this, in turn, affects the stability and accuracy of the ADCPs attached to them.

3.1 Moor Postures in the Water

A critical aspect of this research is understanding how tidal currents affect the deflection of the EAB and SMB mooring systems. Tidal currents can induce significant vertical and lateral movements in moored instruments, which may influence the accuracy of current measurements. To investigate this, this study compares the vertical movements of the ADCPs with tidal elevation data derived from the TPXO tidal model (Egbert & Erofeeva, 2002). The results, illustrated in Figure 4, reveal a clear coherence between the ADCPs' vertical movements (represented by blue lines) and the spring/neap tide variations (indicated by red lines). This coherence suggests that tidal forces play a substantial role in influencing the vertical displacement of the ADCPs, which could lead to missing data and biases in the recorded data. During the two-year experiment, the SMB exhibited a more stable depth variation compared to the EAB, particularly during the summer months (from May to October) when the Kuroshio current is generally stronger. The depth of the EAB varied between 340 m and 380 m (a difference of nearly 40 m) during spring tide in the summer, while the SMB's variation was within 8 m under similar conditions. The SMB's ability to maintain a more stable position during this time is likely due to its design, which is better suited to withstand the forces exerted by stronger and variable currents. This stability is crucial for ensuring that ADCPs can collect full-depth coverage and high-quality data, as excessive vertical movement can result in missing data and biases (Scannell et al., 2022) at different depths.

In contrast, during the winter months, the observations found that both the EAB and SMB experienced more significant fluctuations in their vertical movements due to the increased current speeds near the depth of both the EAB and SMB. Despite this, the SMB still demonstrated a relatively more stable posture compared to the EAB. The significant depth variation of the SMB around 2024/1/1 varied between 313 m and 340 m (a maximum difference of nearly 37 m). In contrast, the EAB showed a larger depth variation of nearly 80 m around January 2023. These findings highlight the importance of selecting an appropriate mooring system based on the specific environmental conditions of the deployment area. In regions with strong and variable currents, such as off southeastern Taiwan, the SMB's superior stability during periods of intense current activity makes it a more reliable choice for long-term oceanographic observations. The study underscores the need for continued research into the design and optimization of mooring systems to improve the accuracy and reliability of data collected by ADCPs, which are vital for understanding and managing marine environments.

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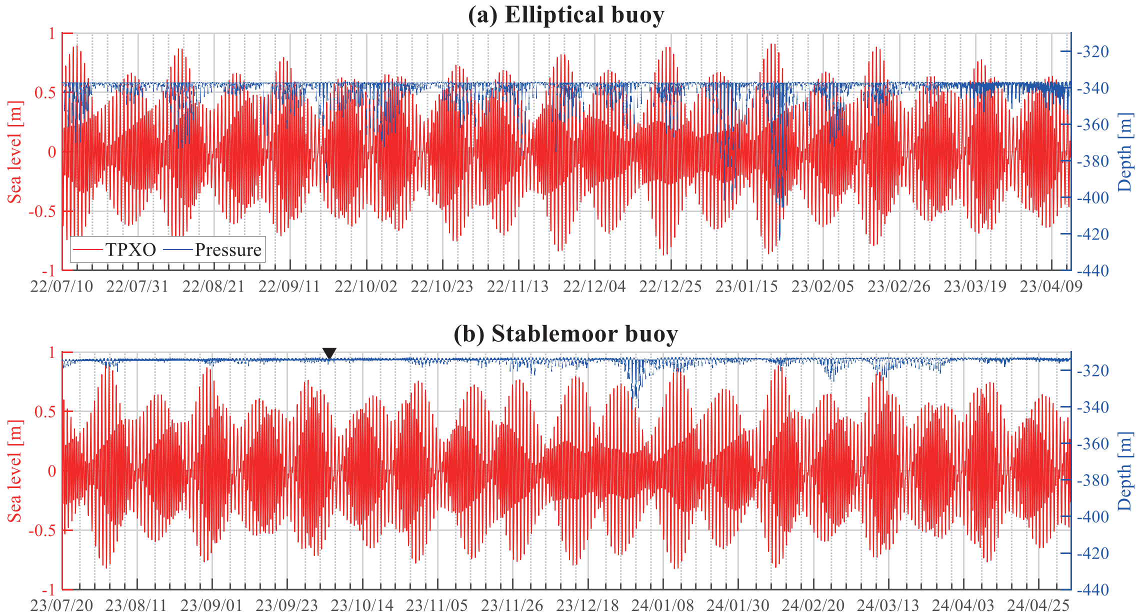

Figure 4. Time series of ADCPs' vertical movements (blue lines) and TPXO elevation (i.e., sea level denoted by red lines) for (a) EAB (phase 1, 2022-2023) and (b) SMB (phase 2, 2023-2024). The black reversed-triangle in (b) represents the day (October 5, 2023) that TY Koinu passed over the ADCP-string.

As previously described, the summer period generally exhibits more stable ADCP postures, particularly with the use of the SMB. However, the winter season introduces more complexity, with greater fluctuations in ocean conditions, leading to more mooring deflection and increased vertical movement of the ADCPs. These unusual cases in the winter months raise important questions about the underlying causes of such significant changes in the ADCPs' posture. Our mooring system was deployed near the generation site of internal waves in the Luzon Strait of the northern South China Sea (Alford et al., 2015). Internal waves, large subsurface waves, can cause significant disturbances in the water column. These waves can blow down the mooring system when passing through and cause short-term hydrographic variations. Although identifying the causes of these short-term variations is not the focus of this study, future studies should delve deeper into this matter.

In addition to these hydrographic factors, another concern is the potential impact of severe tropical cyclones on the local ocean currents and, consequently, on the ADCPs' posture. Tropical cyclones, with their intense winds and associated storm surges, can significantly alter the ocean's upper layers, potentially leading to changes in the ADCPs' positioning. A notable example is Typhoon Koinu (TY-202314), which formed off the eastern coast of Luzon on September 29, 2023. Within two days, Typhoon Koinu intensified into a mid-level typhoon, with maximum wind speeds at the typhoon center exceeding 37.2 m s-1 on a Category-4 typhoon track as it continuously approached Taiwan. By the time it passed over the location of the ADCP-string on October 5, its maximum wind speeds reached over 60 m s-1 2023, as depicted in Figure 5. Despite the strong near-surface wind shear generated by Typhoon Koinu, the ADCP's stance in the water did not exhibit significant movement since Typhoon Koinu only affected the upper 200 meters, showing the relative stability of the ADCP under the robustness of the SMB design during the summer months, when typhoons are more common. The SMB appears to be particularly effective in maintaining the ADCP's stability even in the face of severe weather events, which could otherwise cause substantial disturbances in the water column.

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In contrast, the significant vertical movements observed during the winter months, especially in the absence of a direct tropical cyclone influence, suggest that different factors are at play during this season. The greater instability of the ADCPs during winter, despite the lack of a typhoon, points to the influence of internal ocean dynamics, such as the internal waves or seasonal changes in current patterns and oceanic stratification. These factors could interact in complex ways to produce the observed drops in the ADCPs' vertical position during winter. In summary, while the SMB demonstrates considerable stability during the summer months, particularly in the face of severe tropical cyclones like Typhoon Koinu, both the SMB and the EAB show significant vertical movements during the winter months. This seasonal difference underscores the importance of considering seasonal and hydrographic variations when deploying ADCPs, as the stability of these instruments can be heavily influenced by both atmospheric and oceanic conditions. Further research is needed to fully understand the winter-specific factors contributing to the ADCPs' posture changes and to optimize mooring designs for year-round stability in such dynamic environments.

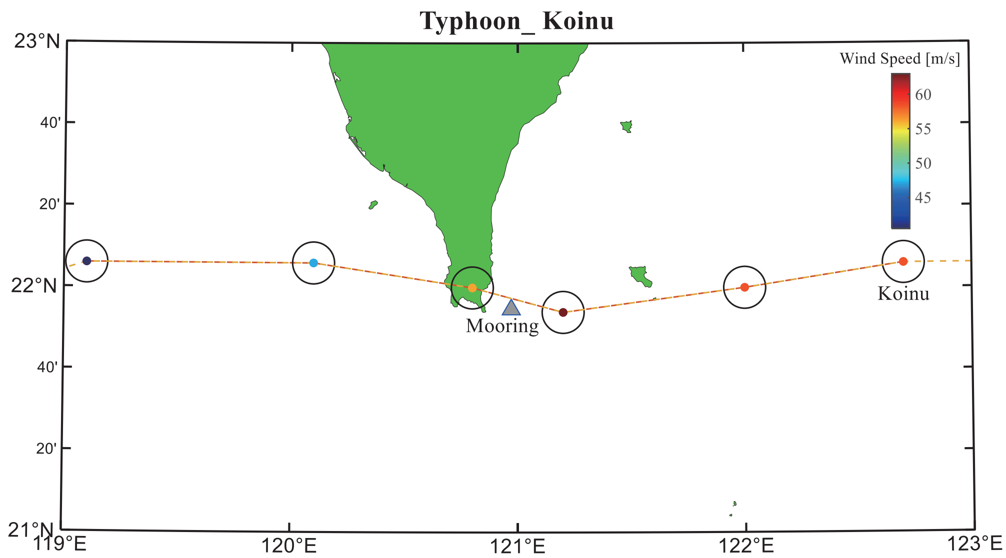

Figure 5. The typhoon track (dashed line) and maximum wind speed at the center (colored dots) of TY Koinu in October 2023.

3.2 Moor Benefits to Data Quality

Figure 6 presents the current speed measurements and percentage good data (PG) values for the ADCPs mounted on the EAB and SMB, respectively. The velocity measurement of the ADCP is based on the reliability of returned signals. The signal correction between two pulses in the pulse pair above 50% is considered a good quality sample (Velasco et al., 2021). The PG is defined as the percentage of "good quality samples" per average, and is tracked during the velocity measurement averaging process. Here, only data with a PG greater than 50% are considered usable (United States. National Ocean Service, 2019) and are displayed in Figures 6a and 6c. A comparison of the datasets on the EAB and SMB reveals remarkably similar performance in measuring current speeds, even in the presence of strong ocean currents. The average current speed recorded by the ADCP on the EAB is 0.259 m s^{-1}, calculated from the first three bins closest to the EAB ADCP at a depth of 324 m. On the other hand, the ADCP on the SMB measures a slightly higher average speed of 0.288 m s^{-1},

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derived similarly from the first three bins nearest to the SMB ADCP at a depth of 293 m. These similar values suggest that both mooring systems are comparably effective in capturing the general flow of the Kuroshio current. The variability of current speeds, as indicated by the standard deviations based on depth-averaged current speeds, provides additional insights into the performance of each system. The standard deviation for the EAB data is 0.171 m s^{-1}, compared to 0.166 m s^{-1} for the SMB data. Although the ADCP on the SMB shows slightly less variation, the small difference in these values reinforces the conclusion that both mooring systems perform similarly. Despite differences in observation periods, the similar standard deviation values indicate that the current speed variability in this region remains relatively stable over time. The time series of current speeds in Figures 6a and 6c further support this conclusion, showing similar vertical variation trends of current speed between the two datasets. Both the EAB and SMB record strong current speeds exceeding 0.6 m s^{-1} (represented by red shading) in the upper ocean layer, approximately 100-150 m deep, and weaker currents at greater depths.

Figures 6b and 6d present the PG values for the EAB and SMB datasets, which is the first data quality control criteria. These three PG categories are broadly defined based on data quality standards, with 85% set as the threshold for the highest data quality (Wang et al., 2003). The PG values in Figures 6a and 6c are further classified into three groups: (1) PG > 85, (2) PG = 70~85, and (3) PG = 50~70 to identify data quality in spatial distribution. A comparison between the EAB and SMB datasets shows that group (1) occupied the upper part of both observations where good quality data started from a depth of 30 meters. However, it is also clear that the EAB displays a wider coverage of lower PG values (group 3) compared to the SMB. The EAB exhibits 5 to 8 depth layers with lower PG values above the instrument, while the SMB has only 3 to 5 depth layers with lower PG values. In other words, better stability of the ADCP buoy leads to better data coverage. This indicates that the SMB provides more reliable and stable measurements with higher data quality compared to the EAB, particularly at greater depths. This consistency in current speed distributions highlights the reliability of both mooring systems in capturing the dynamic behavior of the ocean, particularly in the upper layers where current speeds are typically the strongest. During the second deployment phase (2023-2024), the original EAB mooring system was replaced with the SMB mooring system, leading to improved data quality. As shown in Table 1, the SMB recorded the PG values reaching 100% in 87.07% of cases - nearly 9 percentage points higher than the 78.3% observed with the EAB. The SMB also outperformed the EAB at all quality levels (≥90%, ≥80%, ≥70%, ≥60%, and ≥50%), demonstrating its superiority in supporting ADCP measurements with higher data quality and coverage.

The design of the SMB not only helps the ADCP maintain a more stable measurement environment at greater depths but also effectively reduces both ADCP oscillation or tilting to eliminate measurement biases in strong currents. These improvements ensure that the ADCP can capture higher-quality data even under challenging ocean conditions. Despite the improved stability of the SMB, certain factors still contribute to measurement uncertainties. Environmental influences, such as internal waves and changes in water density, can introduce variability in the ADCP data. Further refinement of mooring systems, or the use of advanced correction algorithms, could help minimize these potential sources of error and improve data accuracy under varying ocean conditions. Overall, these findings suggest that the EAB and SMB are both effective tools for ocean current observation, with comparable accuracy and stability.

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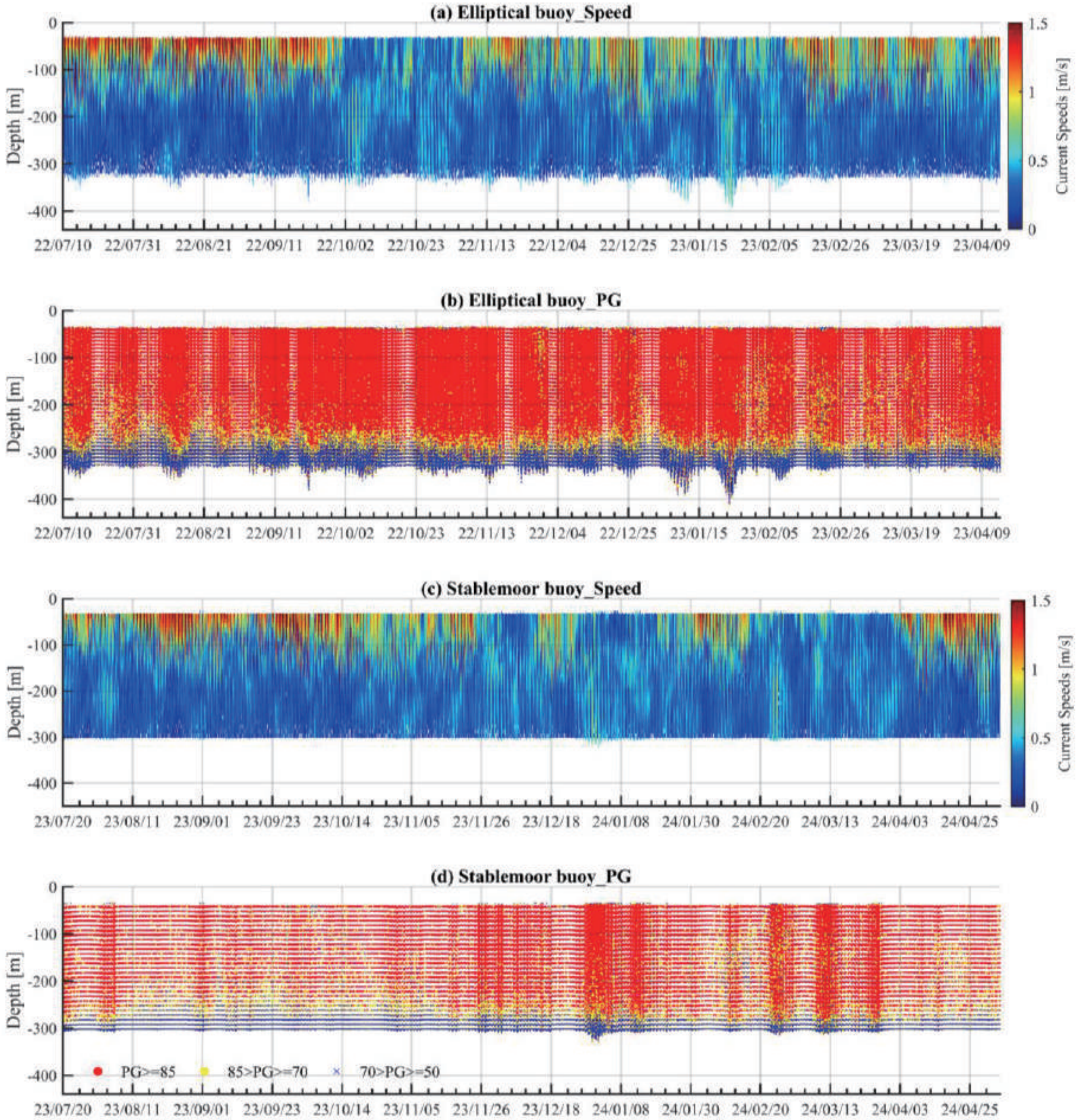

Figure 6. Time series of ADCPs' current speed (color shading) and data percentage good for the (a) and (b) EAB (phase 1, 2022-2023) and (c) and (d) SMB (phase 2, 2023-2024).

Another method for assessing data quality involves analyzing the PG diagrams, which visually represent the proportion of valid data collected by the ADCPs at various depths. These diagrams help illustrate the reliability of measurements across different ocean conditions. As shown in Figures 6b and 6d, PG values exceed 70% across the depth range of 40–250 m for both mooring systems, indicating that both the EAB and SMB are capable of supporting ADCPs in capturing high-quality current measurements in the presence of the strong Kuroshio current. In the first three bins of EAB measurements, 37% of the measurements were bad quality data (PG less than 50%). In contrast, the SMB only measured 9.9% of bad quality data. This difference suggests that the SMB's design provides a more stable platform for the ADCP, enabling it to maintain higher data quality in regions where the EAB might struggle. The SMB's enhanced stability at these depths is likely due to its better ability to counteract strong currents and other environmental factors, reducing the vertical and horizontal movement of the ADCP and allowing for more accurate measurements.

Overall, the PG values from both datasets demonstrate that the EAB and SMB mooring systems perform comparably well in supporting ADCP measurements from near the surface down to about 250 m. Both systems show a high percentage of good data, indicating reliable performance in capturing the dynamics of ocean currents. However, the SMB's superior PG values at depths of 250-300 m underscore its advantage in providing more higher quality data at greater depths, making it a more robust choice for environments with strong currents.

Table 1. Statistics of PG calculated by EAB and SMB datasets.

Buoy type / Date	EAB / 2022-07-05 ~ 2023-04-15	SMB / 2023-07-20 ~ 2024-05-04
Number of measurements	1,496,972	1,124,625
PG = 100	78.3%	87.07%
PG >= 90	86.39%	91.02%
PG >= 80	89.91%	93.55%
PG >= 70	92.56%	95.47%
PG >= 60	94.79%	96.94%
PG >= 50	96.57%	98.77%

3.3 Stability Analyses of the EAB and SMB

Throughout the observation period, both buoys were subjected to strong and highly variable velocities in the Kuroshio current. The SMB demonstrated superior performance compared to the EAB. This advantage is clearly illustrated in the histograms of ADCP headings for both the EAB and SMB, as shown in Figure 7. Despite being deployed at the same location, the datasets from the two buoys reveal a noticeable difference in how they capture the direction of the prevailing Kuroshio current. During the summer, when the Kuroshio current is most dominant, its direction typically flows north to northeast, within a range of 20-40^{o}. While both the EAB and SMB ADCPs capture this general pattern, a more detailed examination of the histograms reveals that the SMB consistently records a higher number of data points within this directional range. Specifically, the SMB dataset shows a peak with a maximum of 2,200 data points, compared to the EAB's maximum of 1,600 data points. This significant difference in data quantity suggests that the SMB provides a more stable and accurate platform for measuring current directions, likely due to its enhanced ability to resist the strong current and maintain a consistent orientation. The heading data is derived from the information collected by the ADCP, and the SMB's torpedo-shaped and cross-vane tail design enables it to resist currents more effectively, with its front facing directly into the current and the tail aligning with the flow direction.

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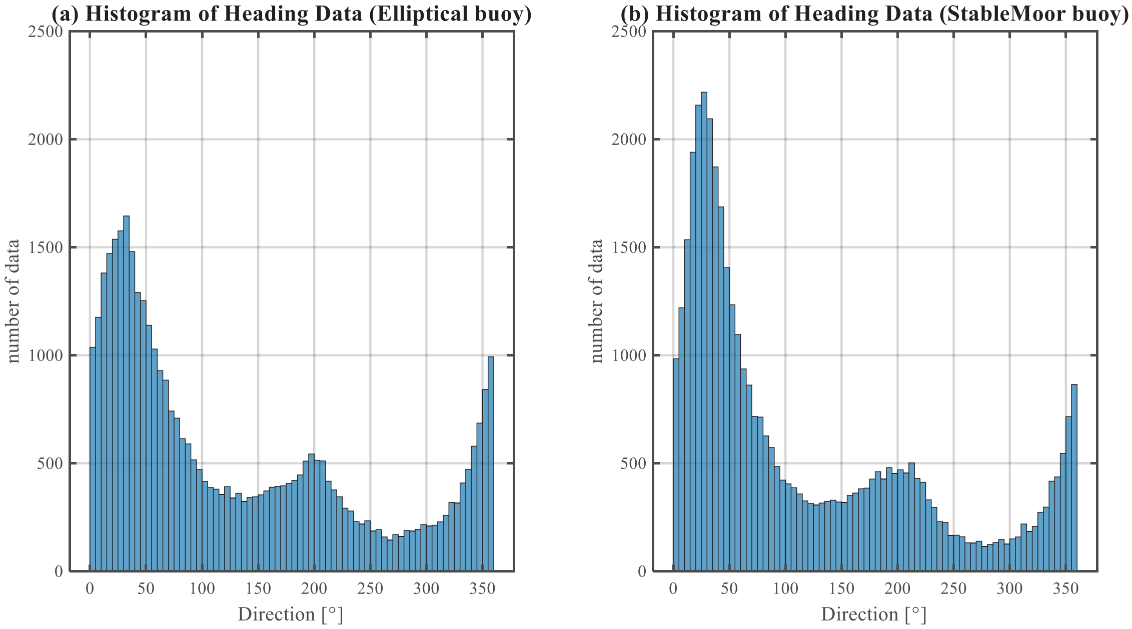

Figure 7. Statistics of ADCP heading for the (a) EAB and (b) SMB.

This finding aligns with previous discussions regarding ADCP vertical movement in section 3.1. The SMB's stability in both vertical positioning and heading allows it to collect more reliable data, even in challenging conditions. This stability is crucial when observing strong currents like the Kuroshio, where accurate directional data is essential for understanding the current's dynamics and their impacts on the surrounding marine environment. The situation becomes more complex during the winter months as the northeast monsoon prevails, affecting both the speed and direction of the Kuroshio current. The monsoon's influence tends to slow down the Kuroshio current and disrupt its typical northeastward flow, occasionally shifting the current's direction toward the south (180-210^{o}). Under these conditions, the ADCP headings on both the EAB and SMB show a similar quantity of data (e.g., about 500 data points) in this southwestward direction, reflecting the seasonal shift in current patterns. Nevertheless, the overall performance of the SMB remains superior, as it continues to capture a higher volume of accurate data points throughout the year, regard less of seasonal changes. In summary, the SMB is a more reliable and effective tool for observing the Kuroshio current, particularly in capturing accurate current directions. Its superior stability allows it to perform better than the EAB, especially in the face of the strong Kuroshio current and the complex conditions influenced by seasonal monsoons. This makes the SMB a valuable asset for long-term oceanographic studies, where maintaining data accuracy and consistency is critical for understanding and predicting ocean current behavior.

Lastly, it is important to analyze the pitch and roll of the two mooring systems to understand the differences in their stability, which highlight the SMB's superior performance in maintaining a steady position in the water. Pitch and roll are critical parameters for evaluating the orientation and stability of moored instruments like ADCPs, as they directly affect the data accuracy. Pitch refers to the tilting motion of the buoy forward or backward, while the roll refers to its side-to-side tilt motion. Ideally, these values should be minimal to ensure that the ADCP remains as horizontal as possible, which is crucial for accurate current measurements.

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Figure 8 presents a clear comparison of the average values and standard deviations of pitch and roll for both systems. Regarding pitch, the EAB has an average value of 0.09°, indicating it generally stays level in the water. In contrast, the SMB shows a higher average pitch of 3°. While this suggests the SMB tilts more than the EAB, the standard deviation must be considered alongside the average. The SMB's pitch standard deviation is only 0.19°, suggesting that despite a higher average tilt, it experiences less fluctuation over time. This consistency in pitch demonstrates the SMB's stability, as it is less influenced by external forces like currents or waves. As for the roll, which is equally critical for maintaining a stable platform, the EAB shows an average roll of 1.24° with a standard deviation of 0.39°. This indicates greater variation in the EAB's side-to-side motion, which could interfere with the ADCP's ability to measure currents accurately. As noted in Scannell et al. (2022), ADCP roll changes the orientation of the acoustic beams, causing the measured velocities to reflect not just the actual water flow but also instrument motion. This interference could impact the accuracy of the EAB's data in dynamic conditions. For comparison, the SMB has an average roll of 1.63°, slightly higher than that of the EAB, but with a much lower standard deviation of 0.17°. This lower variability in roll standard deviation implies that the SMB's roll is much more stable, with less variability in its side-to-side tilting. This reduced variability is critical for ensuring the ADCP remains level, particularly in dynamic ocean environments where strong currents and wave action could otherwise lead to significant tilting. This lower variability in roll suggests the SMB maintains a more stable orientation in the water, which is essential for minimizing high-frequency noise and ensuring the ADCP remains level in dynamic ocean environments. The lower standard deviations in both pitch and roll demonstrate the SMB's overall superior stability compared to the EAB. Even though the SMB shows slightly higher average values for pitch and roll, its ability to maintain a more consistent orientation in high-energy environments like the Kuroshio current ensures more accurate and reliable current measurements.

In contrast, the EAB's greater variability in roll and pitch indicates higher susceptibility to external forces, leading to more frequent and significant tilting, which could compromise data accuracy. Overall, the comparison of pitch and roll between the SMB and EAB clearly demonstrates the SMB's superior stability. This ability to maintain a more consistent orientation, even under challenging conditions, makes it a more reliable choice for long-term oceanographic measurements, particularly in regions with strong and variable currents like the Kuroshio current. While the findings of this study demonstrate the superiority of the SMB in strong current regions like the Kuroshio current, its applicability in other marine environments with different hydrodynamic conditions, such as regions with weaker currents or more complex topography, requires further investigation. Additionally, the performance of the SMB under extreme weather conditions, such as typhoons or severe storms, remains a subject for future study. As a result, while the SMB proves effective for stable and accurate data collection in the Kuroshio current, its broader use in global oceanographic studies should be approached with consideration of these regional and environmental factors.

The stability of data collected by the SMB is particularly valuable for long-term oceanographic monitoring. Accurate and consistent current direction measurements are crucial for understanding large-scale ocean dynamics, such as the Kuroshio's seasonal and interannual variability. This information is not only essential for climate change studies but also for managing marine ecosystems and resources. Ocean currents significantly influence global heat transport and marine life distribution, and reliable long-term data supports more accurate predictive models for future ocean behavior in response to climate change. Therefore, the SMB's enhanced stability and data accuracy make it an essential tool for ongoing oceanographic research and for informing global climate and environmental management strategies.

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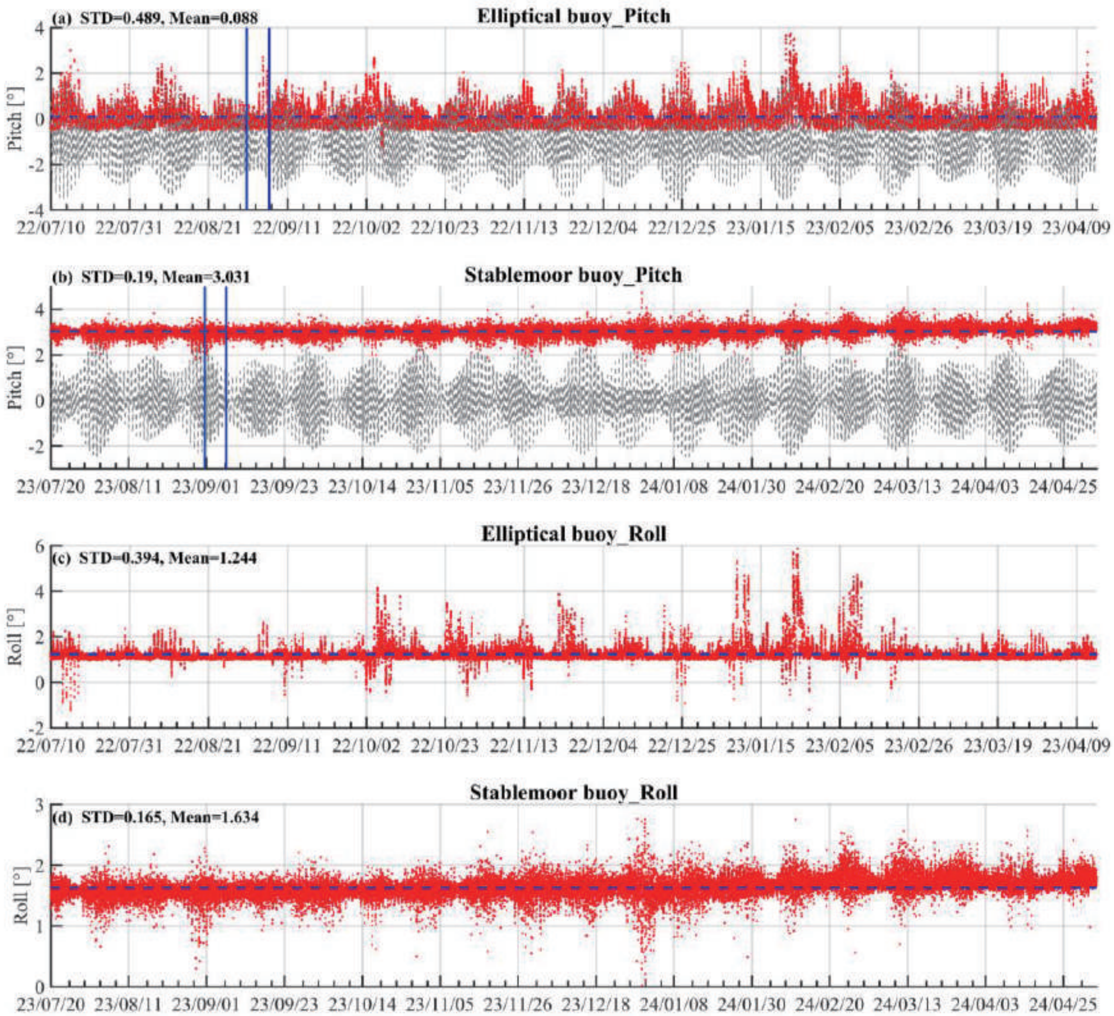

Figure 8. Time series of (a) and (b) pitch and (c) and (d) roll data. Moreover, (a) and (c) are EAB dataset, while (b) and (d) are SMB dataset.

Figure 8 highlights key differences between the two buoy systems, especially during the period indicated by the blue lines, with further details illustrated in Figure 9. During September 1-7, 2022, averaged depth of the first three bins of the EAB ranged from 370 to 390 m, with a corresponding maximum current speed of 0.6 m s^{-1}. In contrast, the SMB during the period from September 1-7, 2023, showed much smaller depth variations, ranging from 380 to 385 m, with a maximum current speed of 0.5 m s^{-1}. These results suggest the SMB maintained a more stable position with the current speed exceeding 0.5 m s^{-1}. Similarly, the EAB's current direction fluctuated by up to 40°, whereas the SMB's variation was limited to 20°, further demonstrating the superior stability of the SMB. During the EAB's observation period, speed direction fluctuated between 20° and 60°, while the SMB data showed a more stable range between 30° and 50°. The greater pitch and roll variations of the EAB resulted in more significant directional changes, whereas the SMB's stability led to more reliable speed and direction data. This demonstrates the SMB's clear advantage in reducing external disturbances and capturing reliable measurements. In addition, the EAB experienced depth variations of nearly 20 m during the observation period, while the SMB showed a much smaller range of 5 m. With the current speed exceeding 0.5

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m s^{-1}, the difference of over 15 m in depth stability highlights the SMB's better ability to maintain a fixed position in the water. Overall, Figure 9 provides a clear comparison of the two systems, showing the SMB's superior performance across all parameters—depth, speed, speed direction, pitch, and roll. The SMB consistently exhibited smaller depth fluctuations (5 meters compared to the EAB's 20 meters), reduced pitch and roll movements, and more consistent current speed and direction measurements.

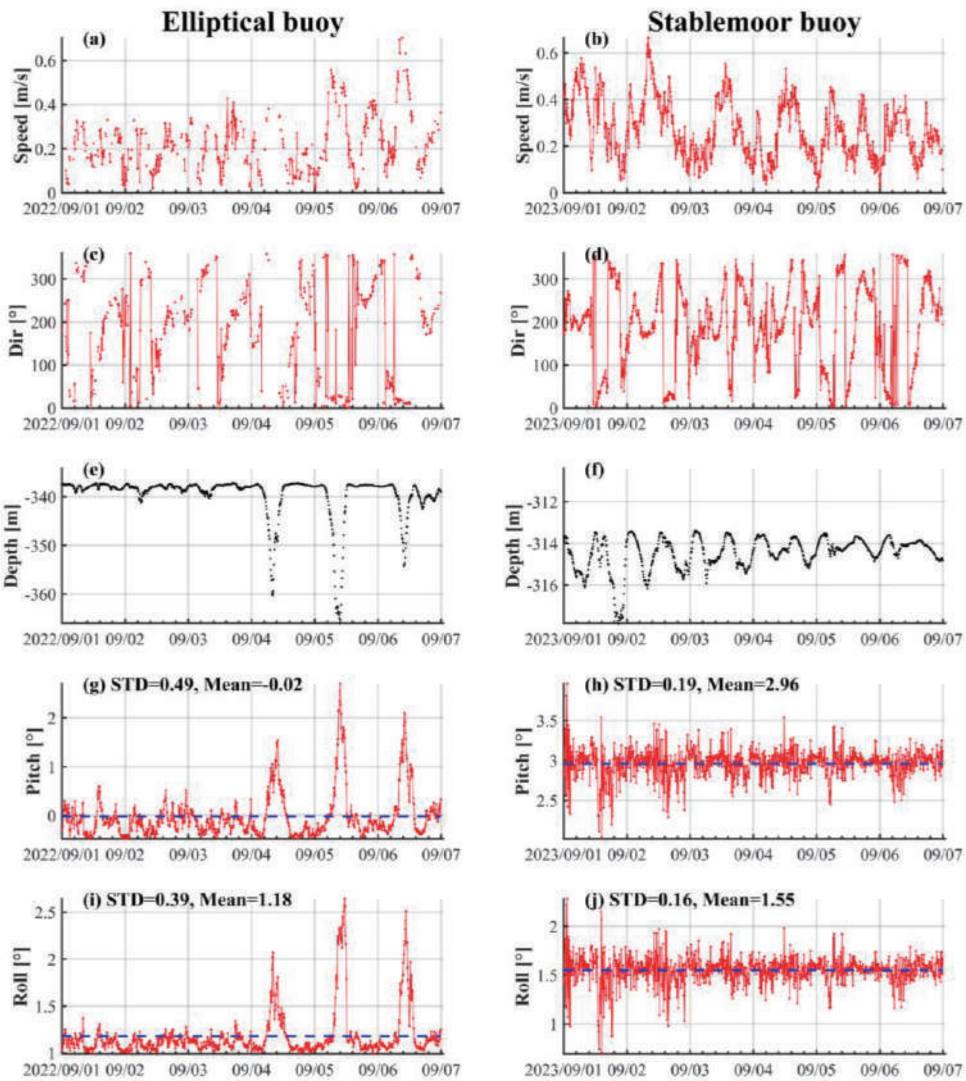

Figure 9. Time series of speed, direction, depth, pitch, and roll from the EAB (September 1-7, 2022) and SMB (September 1-7, 2023) datasets.

4 CONCLUSIONS

The quality of ADCP data is susceptible to interference from subsurface mooring deflection, especially in dynamic aquatic environments. The deployment of the SMB mooring system for the first time in Taiwan represents a significant advancement in addressing these challenges, especially in the context of the strong Kuroshio current or internal waves. By stabilizing the ADCP, the SMB substantially improves data quality and reliability. This study marks the first independent use of the SMB in Taiwan, highlighting a technological milestone for Taiwan's growing capabilities in marine science. This achievement is especially important in regions like the Kuroshio current, where strong and variable currents make accurate ocean current measurements crucial for understanding marine dynamics. Moreover, the SMB's demonstrated its ability to maintain stability in harsh conditions, such as those experienced during Typhoon Koinu, reinforcing its effectiveness in ensuring reliable ADCP data in areas with intense currents.

The key advantage of the SMB lies in its ability to resist the mooring deflection, particularly in the vertical movement. This stability is essential for maintaining a consistent position relative to the water column, which is crucial for accurate and full coverage data collection. Vertical movement can negatively impact the ADCP's readings of pitch, roll, and heading, degrading the PG metric, which evaluates data quality. By reducing these movements, the SMB ensures that the ADCP can collect more accurate data, especially in regions with strong currents like the Kuroshio. The SMB's stability prevents the displacement of subsurface mooring systems, which would otherwise compromise data integrity. In addition to stabilizing the ADCP, the SMB also enhances data coverage across varying depths. While the ADCP measures water currents at multiple layers within the water column, the quality of these measurements depends on the stability of the instrument. Without the SMB, the ADCP may intermittently capture data from certain depths, leading to missing data (gaps) or inaccuracies in the dataset. The SMB, however, allows the ADCP to maintain a consistent underwater position, enabling continuous and comprehensive data collection. This improvement in data coverage is particularly valuable for long-term observation projects, where consistent data is necessary to monitor ocean dynamics accurately.

In comparison to the EAB, the SMB's superior performance especially during the summer months, further highlights its value. Although the EAB is useful, it cannot match the SMB's stability in rough ocean conditions. This is particularly important in areas like the Kuroshio, where strong currents and wave action present significant challenges for subsurface mooring systems. The SMB's resilience to these conditions ensures the consistent collection of high-quality data, regardless of seasonal or environmental changes. The deployment of the SMB in Taiwan provided an opportunity to test its effectiveness in a real-world scenario, such as the strong and variable currents of the Kuroshio. The successful deployment and recovery of the SMB underscore Taiwan's advancement in marine science and technology, providing valuable experience for future long-term ocean observation projects. By using both traditional EABs and the innovative SMB, researchers were able to secure continuous, high-quality data collection year-round, unaffected by seasonal changes or unforeseen oceanographic events. This comprehensive approach to observing the Kuroshio current is essential for advancing our understanding of its annual variability and its broader impact on regional and global ocean circulation. The data gathered during this two-year field experiment will significantly contribute to better modeling and predicting of the Kuroshio's behavior, which is essential for weather forecasting, climate studies, and marine resource management in the region.

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Furthermore, improved data coverage with depth is particularly valuable in complex aquatic environments, where water currents can vary significantly between different layers of the water column. For example, in estuarine environments where freshwater mixes with saltwater, currents can differ dramatically between the surface and the bottom. Accurate data from all depths is essential for understanding these environments and making informed decisions about marine resource management, coastal development, and environmental protection. The SMB ensures that the ADCP can capture critical data with high precision and consistency, making it an invaluable tool for studying such environments. In conclusion, the use of an SMB when deploying an ADCP offers two primary benefits: improved stability, which reduces subsurface mooring deflection and enhances data quality, and improved data coverage, which ensures more comprehensive and reliable measurements across different depths. These advantages not only improve our understanding of mooring system performance in dynamic marine environments but also provide a strong foundation for future advancements in ocean current monitoring and marine resource management. The successful deployment and operation of the SMB serves as a valuable example of how innovative mooring designs can significantly advance oceanographic research, particularly in regions critical to global ocean circulation, such as the Kuroshio current. The SMB has thus proven to be an invaluable tool for researchers and professionals who rely on ADCP data to effectively understand and manage aquatic environments.

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