Characteristics of Sea Surface Current in the Bali Strait, Indonesia using HF Radar and Its Utilization in Safety Navigation

E Supriyadi¹, R Hidayat², IP Santikayasa² and A Ramdhani¹
¹Meteorology Climatology and Geophysics Agency (BMKG), Indonesia
²Department of Geophysics and Meteorology, IPB University, Indonesia
Email: eko.supriyadi@bmkg.go.id

Abstract. This paper was done by using the HF Radar data from 2018-2019 to study the characteristics of Sea Surface Current (SSC) in the Bali Strait. The data processing method was done by calculating the speed and SSC direction of the zonal and meridional components. Furthermore, SSC analysis was performed every hour and month by calculating the average of all data at the same hour and month. It was found that the unique SSC pattern in the Bali Strait occurred on the western side of Bali Island and the eastern side of Java Island. On the west side of the Bali Island, there was a decrease in SSC speed at 0.00-7.00 and 13.00-18.00, as well as a two-fold increase at 8.00-12.00 and 19.00-2.00, both of which were in a fluctuating speed range from 0-140 cm s⁻¹ in the direction of dominant towards the south. On the eastern side of Java Island, SSC speed ranges from 0 to 40 cm s⁻¹ all the time with the dominant direction heading from east to southeast. The monthly SSC pattern was also seen more clearly in this study, meanwhile during December-March the SSC rate was lower than during June-September, ranging from 0 to 20 cm s⁻¹ and from 40 to 140 cm s⁻¹, respectively. Furthermore, the two SSC patterns above can be simplified into two periods, namely periods of relaxation and agitation. This study also applies the device to ship accidents that occurred in the Bali Strait as case studies.

Keywords: sea surface current, Bali Strait, HF Radar, navigation.

1. Introduction

The history of the HF Radar development as an SSC measuring device can be traced back to the 1950s. Crombie [1] studied the reflection of radio waves from the ocean surface by radar at a frequency of 13.56 MHz. For the first time it was discovered that the ocean's wavelength was half the length of radio waves and the change in the Doppler frequency was constant regardless of the surrounding wind and sea conditions. This opens up further research on the use of HF Radar at sea level. The peak was from 1970 to 1980. HF Radar was rapidly developed and became commercially available in the 1980s [2–5]. Until now, there have been two manufacturers that produce HF Radar products, namely the Coastal Ocean Dynamic Application Radar (CODAR) Seasonde and the Welten Radar (WERA) [6,7].

Since September 2018, the BMKG has had two HF Radars installed and fully operational in Indonesia waters, those are in the Bali Strait and in the Flores Sea. The program is part of strengthening the maritime information service system that is currently running at the BMKG Marine Meteorology Center. This implies that the SSC information is easier to obtain at this time. Previously, the SSC research in Indonesian waters mostly used satellites, models and international collaborative research [8–11]. However, the use of HF Radar data and its publication has never been carried out in Indonesia. In fact,
the use of this tool has been used by many countries, such as America (east, west and gulf coast), Korea and Japan in various sectors. The three countries used the most HF Radar at 144, 26, and 22, respectively. It was recorded that until March 2019 there were 400 HF Radar installed to observe the SSC. The devices is spread across 42 countries with 10 countries that partially participate in the global data dissemination and can be accessed at http://global-hfradar.org/[12].

The Bali Strait as the SSC observation location from HF Radar is the water that is separated by Java Island in the west and Bali Island in the east, respectively, bordering the Java Sea and Indian Ocean. The topography of this strait is in the form of an inverted cone, which is narrowing on the north side and enlarging on the south side. From the bathymetric profile, it is obtained that the seabed slope of the strait is directed to the south. Several studies related to atmosphere-ocean conditions in the Bali Strait have been carried out, such as: Hendiarti [13] examined upwelling events in the Bali Strait reaching its maximum in the eastern monsoon; and the effect of water level and wind speed on the SSC characteristics by Supriyadi [14]. Furthermore, Saragih [15] also found that during the eastern monsoon, the water mass in the northern part of the Bali Strait does not look uniform and the water mass in the southern part of the Bali Strait looks the other way. In addition, it was also explained that SSC in the Bali Strait is associated with the incidence of the west and east monsoons.

Furthermore, the need for SSC information is indispensable for marine information users, such as fishermen, aquaculture farmers, the tourism sector, local government, search and rescue, and coastal communities. In some cases, information about the SSC characteristics can help search and rescue teams in the event of an accident at sea. For example, the oil spill in Balikpapan Bay in March 2018, the crash of a Sriwijaya airplane in Jakarta Bay on January 9, 2021, and events that often occur and have a significant impact such as decreased sea catch for fishermen due to changes in currents. Unfortunately, before the HF Radar was installed, there was no sufficient SSC data available to analyze the cases mentioned. So, this study aims to find the SSC characteristics using HF Radar in the Bali Strait, its application in cases of ship accidents and offers novelty in the form of its utilization in Indonesia waters.

2. Methodology
The data used in this study came from HF Radar measurements located in the Bali Strait from October 2018 to April 2019 (Figure 1). The data were obtained from the Marine Meteorology Center, BMKG. The data used are still in the form of special HF Radar extension, that is *.tuv. So, it still needs further processing to produce surface current components, in this case it will be converted into *.nc format.

![Figure 1](image.png)

**Figure 1.** The HF Radar network in the Bali Strait is marked with red dot (a). Availability data (%) use in this study from October 2018-September 2019 (b). Blue radial in the map is the range of devices.
Every single nc file that has been converted contains three main variables, that are latitude-longitude, time, and the zonal-meridional component of the current. The SSC speed calculation is performed to perform zonal and meridional resultants:

$$\text{current} = \sqrt{u^2 + v^2}$$  \hspace{1cm} (1)

When $u$ is the zonal current component and $v$ is the meridional current component. Furthermore, the calculation of the current direction ($\theta$) is carried out with the equation:

$$\theta = \arctan \frac{v}{u}$$  \hspace{1cm} (2)

Pay attention to the Press. (2) the resulting angle reference is the east direction. However, in the world of shipping, the angle reference is the north direction. So that the equation (2) modified to:

$$\varphi = 90 - \theta$$  \hspace{1cm} (3)

During measurement, HF Radar conducted SSC observations every 30 minutes. To analyze the hourly and monthly SSC, the average calculation was performed at the same hour and month from all data. The equation used show in equation (4) with $n$ is the number of HF radar data

$$\text{current} = \frac{\sum_{i=1}^{n} \text{current}_i}{n}$$  \hspace{1cm} (4)

3. Results and Discussion

3.1 Bali Strait diurnal SSC pattern

The diurnal pattern of the Bali Strait SSC is presented in Figure 2-3. In general, the fluctuating SSC speed occurred on the western side of the Bali Island with a two-fold decrease from 0.00 to 7.00 and 13.00 to 18.00, and a twofold increase from 8.00 to 12.00 and from 19.00 to 2.00. For the dominant SSC direction was towards the south, except at 5.00 to 6.00 where the current was relatively calm and tended to move to the north. Meanwhile, on the eastern side of Java Island, SSC speed tended to be low and did not fluctuate with the dominant SSC heading from east to southeast, except from 4.00 to 7.00 and 15.00 to 18.00 when the direction of SSC to the north. The difference in the direction of the SSC on the east side of Java Island and the west side of the Bali Island resulted in eddy in the south of the Bali Strait at the two times intervals.

At 0:00, high SSC speeds occurred on the west side of Bali Island with a range of 120–140 cm s$^{-1}$, where at Gilimanuk Port itself it reached 122 cm s$^{-1}$. For the Java side, SSC speeds were relatively quiet at 0–40 cm s$^{-1}$, with SSC speed at Ketapang Port with a value of 17 cm s$^{-1}$. The direction of SSC currents is dominated to the south for the west side of Bali Island, but on the east side of East Java the direction of the current tends to the southeast which then joins the direction of the dominant current to the south. The current pattern at 1:00 is similar to that of 0.00 except that it has decreased in speed. At 2.00 the SSC speed at Gilimanuk and Ketapang ports was 82 and 22 cm s$^{-1}$, respectively, with the SSC direction predominantly heading south on the west side of Bali Island. However, on the eastern side of Java Island, the direction of the current is to the east and then moves towards the north. A similar SSC direction pattern continued until 3.00am with a decreasing speed at 0–40 cm s$^{-1}$.

During 3.00 to 8.00 the SSC velocity in the Bali Strait tends to be low with a value range of 0–40 cm s$^{-1}$. However, during 5.00 to 7.00 the SSC direction on the west side of Bali Island was different from the previous time, which was heading east to north. Even during 4.00 to 7.00 there was an eddy in the middle of the waters of the Bali Strait. Starting from 8.00 the SSC speed at Gilimanuk port increased again by 49 cm s$^{-1}$ with the dominant SSC heading south. The SSC velocity increases proportionately until it reached its peak at 12.00 within the range of 120-140 cm s$^{-1}$ on the west side of Bali Island. Furthermore, the SSC speed decreased again from 13.00 to 19.00 in the range of 0–40 cm s$^{-1}$. There is an interesting thing from the resulting SSC direction at 16.00 and at 17.00. It was when the meeting of the north current direction on the eastern side of Java Island causes an eddy in the middle of the Bali Strait with the direction of the south current on the west side of the island of Bali.

At 19.00 the SSC speed on the Bali Island side increased again within the range of 20–40 cm s$^{-1}$. Then it increased gradually until it reached a speed of 120–140 cm s$^{-1}$ at 23.00. with the dominant SSC heading south. The entire cycle above continued over the course of one day.
Figure 2. Diurnal of the SSC pattern in the Bali Strait at 0.00-11.00 local time. Quiver and contour are expressed direction and speed of the SSC.
Figure 3. Continues from Figure 2 but for 12.00-23.00 local time
From the analysis above, it was found that the SSC velocity fluctuation in the Bali Strait is similar to the tidal pattern that occurs in these waters. The tide data collected from Pushidrosal (Navy Center for Hydrology and Oceanography) Indonesia, shows that there were two times the tide and the ebb in one day (Figure 4). If we look at all of Figure 4, the SSC direction in the Bali Strait generally goes to the South. This was due to the influence of the bathymetry of the Bali Strait which leads to the Indian Ocean. Research conducted by Berlianty and Yanagi [16] states that the bathymetry of the north side of the Bali Strait was relatively shallow at around 20 m and gradually increases to 700 m on the southern side of the water.

![Figure 4. Hourly mean tidal data from 1 October 2018-30 September 2019 (data re-calculate from Indonesia Geospatial Information Agency, BIG).](image)

3.2 Monthly the SSC pattern in the Bali Strait

This section describes the monthly SSC pattern in the Bali Strait. Starting at the Bali Strait, which is a crossing route between two islands with two main ports, the Port of Ketapang (Bali) and Gilimanuk (East Java). In Figure 5, generally, the SSC velocity ranges from 0–60 cm s\(^{-1}\), except that in October when it was detected that in Gilimanuk Port it was able to reach 100 cm s\(^{-1}\). Generally, the SSC direction is predominantly directed to the South towards the Indian Ocean. However, in some areas, such as the northern side of the Bali Strait, it headed to the north.

In October, it was marked by strong currents around Gilimanuk Port reaching 78 cm s\(^{-1}\). On the other hand, at Ketapang Port the current is lower, that is 14.5 cm s\(^{-1}\). On the Bali coast, the SSC tends to lead to the south. The direction of this current then headed to the southeast when it met the SSC originating from the East Java coast. SSC speed on the East Java coast tends to be relatively calm in October. It is characterized by two eddies, one that leads to the west in the north and one that leads to the east on the south coast of East Java.

In November the SSC speed in Gilimanuk Port was greater than Ketapang Port, by 51 and 4 cm s\(^{-1}\), respectively. On the Bali coast, the SSC direction, apart from heading to the south, also turned towards the north to further form a vortex on the northern coast of East Java. On the coast of East Java, the SSC initially headed to the east, but in the middle, the waters were divided into north and southeast directions. The effect is to produce two eddies in the central and southern parts of the Bali Strait.

In December, the current velocity at Gilimanuk Port was still greater than at Ketapang Port, by 37 and 13 cm s\(^{-1}\), respectively. On the Bali coast, the SSC direction is different. The SSC direction on the northern coast of Bali is to the south, but in the middle the waters are divided into two, to the east and south. In the southern part, the formed SSC is unique. Instead of forming an eddy as a resultant from the East Java coastal SSC that leads to the southwest, it also forms a second vortex in the southern part of the Bali Strait waters. Compared to November, the swirl that occurred this month is closer to the Bali Island.
Figure 5. Monthly of the SSC pattern in the Bali Strait. Quiver and contour are expressed direction and speed of the SSC.
The SSC velocity pattern in January was almost the same as the SSC pattern in December, which is dominated by the 0–20 cm s⁻¹ interval. However, now, the current velocity at Gilimanuk Port is weaker than at Ketapang Port, respectively 23 and 45 cm s⁻¹. From the observations to the direction and velocity of the SSC, it appears that it is relatively calmer in the middle of the water until it approaches the coast in Bali. Meanwhile, on the East Java coast, the SSC direction is generally constantly to the north. A minimum velocity current was detected 5 cm s⁻¹. Both in December and in January, the SSC in the Bali Strait is calm. So that it really supports inter-island shipping activities in particular.

Entering February, the SSC again showed fluctuation. It can be seen in Figure 5 that in the middle part of the waters to the Bali coast, the direction of the current that occurs entirely southwards with a maximum speed of 67 cm s⁻¹ occurs at Gilimanuk Port. This result is different when compared to the East Java coast, which is relatively low, within the range of 0–20 cm s⁻¹. The SSC direction at this location heads east and then returns calm in the middle of the water.

Furthermore, in March the SSC velocity pattern was almost the same as the SSC pattern in February. It is high on the Bali coast and low on the East Java coast. In this month, the SSC velocity at Gilimanuk and Ketapang Ports was 59 and 24 cm s⁻¹, respectively. While the direction is predominantly towards the south, especially the Bali coast. On the East Java coast, the SSC velocity is relatively lower, that is 0–20 cm s⁻¹ with an eastward and partly northward direction. The lowest SSC velocity was detected at 5 cm s⁻¹ in the middle of the water.

A different view from the previous month occurred in April on the East Java coast. In this month, the minimum current velocity can reach the value ranging from 40 to 60 cm s⁻¹. However, the SSC direction is still heading east to further join the SSC currents on the Bali coast to the south. The SSC velocity in Gilimanuk Port was greater than in Ketapang Port, by 83 and 11 cm s⁻¹, respectively. In May, the SSC speed at Gilimanuk Port was detected greater than at Ketapang Port, by 78 and 18 cm s⁻¹, respectively, with dominance to the south. This pattern then dominates the entire western Bali coast. For the East Java coast, two different current directions were detected. First, the direction of the current from the north and turning toward the east. Second, currents from east to southeast which further merge and strengthen with the SSC from the western Bali coast.

There is a different view for SSC in June. It can be seen that the maximum current velocity occurs on the western Bali coast and it can reach 120 cm s⁻¹. The SSC speed at Gilimanuk and Ketapang Ports was 96 and 30 cm s⁻¹, respectively. The current pattern this month is predominantly directed south on the western Bali coast. Meanwhile, on the eastern East Java coast, the direction of the current is towards the west (mainland) and towards the east (middle waters) which then joins the SSC from the western Bali coast.

When compared to the previous month, the maximum SSC velocity occurred in July on the Bali coast and could reach 140 cm s⁻¹, with a wide water coverage, from 8.16° to 8.20° east latitude. In this month, the SSC velocity at Gilimanuk Port is in contrast to the Ketapang Port, each of 124 cm s⁻¹ and 11 cm s⁻¹. The current pattern is still dominated towards the southern part of Bali coast and partly towards the northern part of East Java coast. Furthermore, the SSC direction and velocity in August and September almost have the same pattern, except that the maximum SSC velocity coverage that is at intervals of 120–140 cm s⁻¹ is much less. The current direction pattern is still the same as in July-September.

If we look at all of Figure 5, the SSC direction in the Bali Strait generally goes to the South. This is due to the influence of the bathymetry of the Bali Strait which leads to the Indian Ocean. Berlianty and Yanagi [16] explained that the bathymetry of the north side of the Bali Strait is relatively shallow, about 20 m and extending to 700 m on the south side of the water. Some of the eddies that are formed during December and February can also be influenced by various things, such as: the influence of the wind [17], the imbalance of the baroclinic layer [18], and differences in salinity [19]. The effect of the moon on SSC seems to be more detected in the Bali Strait. In addition, during December and March SSC velocity was lower than in June-September.

Specifically, the SSC velocity in the Bali Strait is divided into relaxation and agitation period. In this study, the relaxation period occurs from November to May and the agitation period occurs from June to October. Several previous studies have also discussed these relaxation and agitation period, such as Largier [20] explaining that relaxation periods occur due to differences in barotropic pressure as a result.
of the upwelling process, while agitation periods are due to storm in the ocean. Gough [21] described relaxation and agitation periods are influenced by fluctuating low and high wind speeds. Pranowo [22] also found that the SSC pattern in the Bali Strait occurred from December to February with an average wind speed of 2-6 m s\(^{-1}\) with a dominant direction to the southeast.

3.3 Case study: Shipwreck in Bali Strait

There have been two ship accidents in the Bali Strait so far. The first case was the Tunu Pratama Jaya 3888 ship that collided with the KMP on the Nusa route at Ketapang Port on May 31, 2019 at 07:00 WIB (Western Indonesian Time). The second case was KMP Agung Samudra IV that shook while loading and unloading at Gilimanuk Port. It caused an egg transport truck to roll on board on May 31, 2019 at 08:00 WITA (Central Indonesian Time) [30, 31]. If we pay close attention, the two events occurred on the same date and time.

Analysis of the SSC contour (Figure 6a) shows that strong currents occur on the west side of Bali Island including at Gilimanuk Port, meanwhile on the east side of East Java Island the SSC velocity is relatively lower. Observations from the current rose diagram (Figure 6b-c) of both at the Ketapang and Gilimanuk ports show that the direction of the current is predominantly directed to the South. The direction of surface currents on the east side of East Java is relatively more even in the eight cardinal directions in the form of a histogram with the most current direction to the southeast, while on the Bali side the direction of the most currents is also dominated to the southeast (Figure 6d-e).

From the analysis, it was found that the ship accidents in the two locations were not influenced by the current factor. Although in Figure 6a the SSC speed is up to 120 cm s\(^{-1}\) dominating around Gilimanuk Port, but when viewed onsite at Ketapang and Gilimanuk Ports, the maximum SSC speed can reach > 120 cm s\(^{-1}\) (Figures 5 at panel May and June), with the most southerly direction during 30 May – 1 June 2019. If the direction of the current is traced in detail, ship accidents at Ketapang Port generally occur when the dominant SSC is heading north, southeast to south. At Gilimanuk Port, the current direction at the time of the ship accident was dominated to the southeast (Figure 6b-c).

The resulting current direction can be used as a subject or particle trajectory at sea level. This is useful especially when the subject who gets involved in an accident above sea level breaks into several particles. An example of a trajectory technique has been carried out by Shen [23] in Taiwan waters to determine the location of missing persons.

![Figure 6](image-url)

**Figure 6.** All analyzed the SSC in ship accident case study in the Bali Strait for 30-31 May, 1 June 2019 such as follow: contour (a), current rose in Ketapang Port (b), Gilimanuk Port (c), current direction at 6.00-8.00 WITA in west strait (d), and east strait (e).
4. Conclusion
The use of HF Radar data to study and analyze SSC characteristics on a diurnal and monthly scale in the Bali Strait, Indonesia has been carried out. On a diurnal scale, the unique characteristics of SSC occur in two locations, that are the western side of Bali Island and the eastern side of Java Island. On the western side of Java Island, the velocity increases and decreases twice in one day, while the eastern side of Java Island is relatively calm throughout the day. Furthermore, the characteristics of SSC in the Bali Strait have different patterns every month. The SSC velocity is smaller from December to February than from June to August. In simple terms, the two velocity patterns are divided into relaxation and agitation periods. Generally, the relaxation period is characterized by varying low and high wind speeds, while the agitation period is triggered by storms that occur in the ocean. In addition, the SSC direction in the Bali Strait is predominantly southward due to the influence of the bathymetry slope.

Furthermore, analysis of ship accidents in the Bali Strait was also done using HF Radar data as real application. Based on the obtained results, the installation of the HF Radar is required in other Indonesian waters, so that the characteristics, phenomena and knowledge of marine weather can be identified properly.

Acknowledgments
The authors expressed thanks to the Marine Meteorological Center, BMKG for availability of HF Radar data, Geospatial Information Agency (BIG) who provide data to produce Figure 4, and also suggestions and assessments of reviewers.

References
[1] Crombie D 1955 Doppler spectrum of sea echo at 13.56 Mc./s. Nature 175 681–2
[2] Barrick D E 1971 Theory of HF and VHF propagation across the rough sea, 1. The effective surface impedance for a slightly rough highly conducting medium at grazing incidence Radio Sci. 6 517–26
[3] Barrick D E 1971 Theory of HF and VHF propagation across the rough sea, 2. Application to HF and VHF propagation above the sea Radio Sci. 6 527–33
[4] Stewart R H and Joy J W 1974 HF radio measurements of surface currents Deep Sea Res. Oceanogr. Abstr. 21 1039–49
[5] Barrick D E and Lipa B J 1979 Ocean Surface Features Observed by HF Coastal Ground-Wave Radars: A Progress Review BT - Ocean Wave Climate ed M D Earle and A Malahoff (Boston, MA: Springer US) pp 129–52
[6] Roarty H, Cook T, Hazard L, George D, Harlan J, Cosoli S, Wyatt L, Alvarez Fanjul E, Terrill E, Otero M, Largier J, Glenn S, Ebuchi N, Whitehouse B, Bartlett K, Mader J, Rubio A, Corgnati L, Mantovani C, Griffa A, Reyes E, Lorente P, Flores-Vidal X, Saavedra-Matta K J, Rogowski P, Prukpitkul S, Lee S-H, Lai J-W, Guerin C-A, Sanchez J, Hansen B and Grilli S 2019 The global high frequency radar network Front. Mar. Sci. 6 164
[7] Liu Y, Weisberg R H and Merz C R 2014 Assessment of CODAR SeaSonde and WERA HF radars in mapping surface currents on the West Florida Shelf J. Atmos. Ocean. Technol. 31 1363–82
[8] Harini W S 2004 Pola Arus Pemukaan di Wilayah Perairan Indonesia dan sekitarnya yang diturunkan berdasarkan data satelit Altimetri TOPEX/POSEIDON (IPB University)
[9] Gordon A 2005 Oceanography of the Indonesian Seas and their throughflow Oceanography 18 14–27
[10] Koch-Larrouy A, Atmadipoera A, van Beek P, Madec G, Aucan J, Lyard F, Grelet J and Souhait M 2015 Estimates of tidal mixing in the Indonesian archipelago from multidisciplinary INDOMIX in-situ data Deep Sea Res. Part I Oceanogr. Res. Pap. 106 136–53
[11] Koch-Larrouy A, Lengaigne M, Terray P, Madec G and Masson S 2010 Tidal mixing in the Indonesian Seas and its effect on the tropical climate system Clim. Dyn. 34 891–904
[12] JCOMM 2019 *High Frequency Radar Network, 10th Session of the JCOMM Observation Coordination Group* (Jakarta)

[13] Hendiarti N, Suwarso, Aldrian E, Amri K, Andiastuti R, Sachoemar S and Wahyono I 2005 Seasonal variation of pelagic fish catch around Java *Oceanography* **18** 112–23

[14] Supriyadi E 2021 *Karacteristik Arus Laut Permukaan di Selat Bali dan Laut Flores menggunakan HF Radar* (IPB University)

[15] Saragih D A 2002 *Studi Karakteristik Massa Air di Perairan Selat Bali pada Bulan Agustus 2000* (IPB University)

[16] Berlianty D and Yanagi T 2011 *Tide and tidal Current in the Bali Strait, Indonesia* *J. Mar. Res.* **36** 25–36

[17] Schaeffer A, Gramoulle A, Roughan M and Mantovanelli A 2017 Characterizing frontal eddies along the East Australian Current from HF Radar observations *J. Geophys. Res. Ocean.* **122** 3964–80

[18] Guo J, Zhang Z, Xia C, Guo B and Yuan Y 2018 Topographic–baroclinic instability and formation of Kuroshio current loop *Dyn. Atmos. Ocean.* **81** 15–29

[19] Brokaw R J, Subrahmanym B and Morey S L 2019 Loop current and Eddy-driven salinity variability in the Gulf of Mexico *Geophys. Res. Lett.* **46** 5978–86

[20] Largier J L, Magnell B A and Winant C D 1993 *Subtidal circulation over the northern California shelf* *J. Geophys. Res. Ocean.* **98** 18147–79

[21] Gough M K, Garfield N and McPhee-Shaw E 2010 An analysis of HF radar measured surface currents to determine tidal, wind-forced, and seasonal circulation in the Gulf of the Farallones, California, United States *J. Geophys. Res. Ocean.* **115**

[22] Pranowo W S 2006 *Sirkulasi arus vertikal di Selat Bali pada monsun tenggara 2004* (Palembang)

[23] Shen Y-T, Lai J-W, Leu L-G, Lu Y-C, Chen J-M, Shao H-J, Chen H-W, Chang K-T, Terng C-T, Chang Y-C and Tseng R-S 2019 Applications of ocean currents data from high-frequency radars and current profilers to search and rescue missions around Taiwan *J. Oper. Oceanogr.* **12** S126–36