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Performance of VMS and nightly satellite in monitoring light fishing vessels in the open South China Sea

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ABSTRACT

With the development of satellite technology, vessel monitoring has entered a new era. In this study, through a comparison with better-recorded fishing logs, we analyzed the performance of vessel monitoring system (VMS) and nightly satellite data in monitoring fishing activities of a large-sized falling net vessel mainly targeting the purpleback flying squid (*Sthenoteuthis oualaniensis*) in the open South China Sea. Logbook data indicate that the studied vessel operated fishing for 57 days in the 3-month fishing season, performing a total number of 474 fishing hauls with ~233.7 tons of catches. Our analysis indicated that with VMS data only, fishing state can hardly be distinguished from the drifting one, while even under the influence of clouds, the nightly satellite can identify most (98 %) of the fishing operations that were emitting bright lights. In addition, catch rates recorded by fishing logs significantly correlated with the numbers of lighted lamps when the nightly satellite passed over, which implies that the radiance may even be used as a proxy for catch. Although the radiance emitting from lighted lamps onboard a fishing vessel and detected by a nightly satellite is influenced by a number of factors, such as cloud conditions and satellite viewing zenith angle, jointly use of VMS and nightly satellite data can be an effective approach in monitoring and managing this type of light fishing vessels.

1. Introduction

The South China Sea (SCS) produced 12 % of global marine fish catch in 2015, with over half of the fishing boats in the world operating there, mostly along the coast (Watson and Tidd, 2018; Zhao et al., 2018). However, with the intensified overfishing in its coastal fisheries, the lightly-exploited and abundant oceanic stocks, mainly the oceanic squid purpleback flying squid (*Sthenoteuthis oualaniensis*), tuna and tuna-like fishes, in the open SCS have attracted interest of the bordering countries, especially China and Vietnam (Siriraksophon et al., 2001; Nigmatullin, 2004; Chen et al., 2008; Zhang et al., 2010; Arkhipkin et al., 2015; Zhang et al., 2015; Yu et al., 2019a).

Due to their positive phototaxis, fishing with artificial lights has developed as a successful method to catch the oceanic purpleback flying squid in the open SCS (Zhang et al., 2013; Nguyen and Tran, 2015; Nguyen and Winger, 2019). China has developed this fishery via deployment of large-sized light falling net vessels since 2004, and now it has ~200 vessels seasonally fishing for the squid during springtime in the open SCS (Zhang et al., 2013; Zou et al., 2014). These open-sea fishing vessels are mostly >35 m in length with total power of >500 kW, equipped with as many as 500–1000 lamps and generating as much as 200–500 kW of lights per vessel during fishing (Figs. 1 and S1). The purpleback flying squid is the major target species for these vessels, whose catch accounts for ~80 % of the total catch in the open sea. Unlike Chinese fisheries using large-sized lighting vessels, Vietnamese open-sea lighting fisheries mainly use lighting purse-seine and hand-line boats (Fig. 1B). Vietnamese boats are much more numerous (~3000) but smaller in size and with fewer lights (total light power usually <20 kW). Additionally, Vietnamese boats fish year-round and mainly target tuna and tuna-like fishes (Nguyen and Tran, 2015).

The recent open-SCS fisheries development has increased the need for monitoring the fishing fleet, for the purposes such as forecasting

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fishing grounds and dealing with illegal, unreported and unregulated activities (Straka et al., 2015; Geronimo et al., 2018; Hsu et al., 2019; Li et al., 2021). Fishing footprint could be achieved by a lot of vessel monitoring methods. The routine to monitor and manage Chinese oceanic squid fishing vessels is based on VMS data transmitted via Beidou navigation system, which provides the position and velocity of a vessel only. The precise fishing positions and catch rates of this type of vessels can hardly be inferred from VMS data. Therefore, with the VMS data alone, it is not sufficient to predict the squid's preferred environmental conditions and areas of abundance. The other effective way to monitor lighting fisheries is via nightly satellite sensors, such as DMSP-OLS and VIIRS-DNB (Rodhouse et al., 2001; Waluda et al., 2004, 2008; Riyanto et al., 2016; Elvidge et al., 2017). The predominant features of these sensors are the detection of lights at night on the earth's surface. The light sources on the ocean surface may come from lit fishing boats, gas flares and platforms. These sensors generally do not pick up weaker light sources such as those from moving and drifting vessels, but detect only those bright lights used to attract fish schools (Hsu et al., 2013; Zhizhin et al., 2017; Hsu et al., 2019). In addition, the bright lights from fixed locations, such as those from gas flares and platforms, can be removed. Hence, a combination of VMS and nightly satellite data may provide better monitoring of the large-sized light falling net vessels.

This study aims to assess the performance of VMS and night-time light remote sensing in monitoring the open-SCS light fishing vessels and their potential in managing oceanic fisheries and predicting the squid's habitat in the open SCS.

2. Data and methods

2.1. Fishing logs

In order to assess the performance of VMS and nightly satellite in monitoring light fishing vessels in the open SCS, we chose a typical Chinese large-sized light falling net vessel "Yuedianyu 42212" with better-recorded fishing logs for validation from the Guangdong Province. The logbook data of this vessel contained more detailed information than ordinary ones and were recorded by an onboard observer. Recorded by the fishing logs were numbers of fishing hauls, lighted lamps, moving time and drifting time for each fishing night, catches, fishing time, and fishing position for each haul. The logs recorded data from a total number of 486 fishing hauls during the spring fishing season from March to June in 2015.

States of activities of this type of vessels can be classified into landing, moving, fishing, and drifting. Landing is indicated by a vessel staying at a port or by a coral reef, moving denotes that a vessel is steaming between fishing ground and its home port, drifting is identified

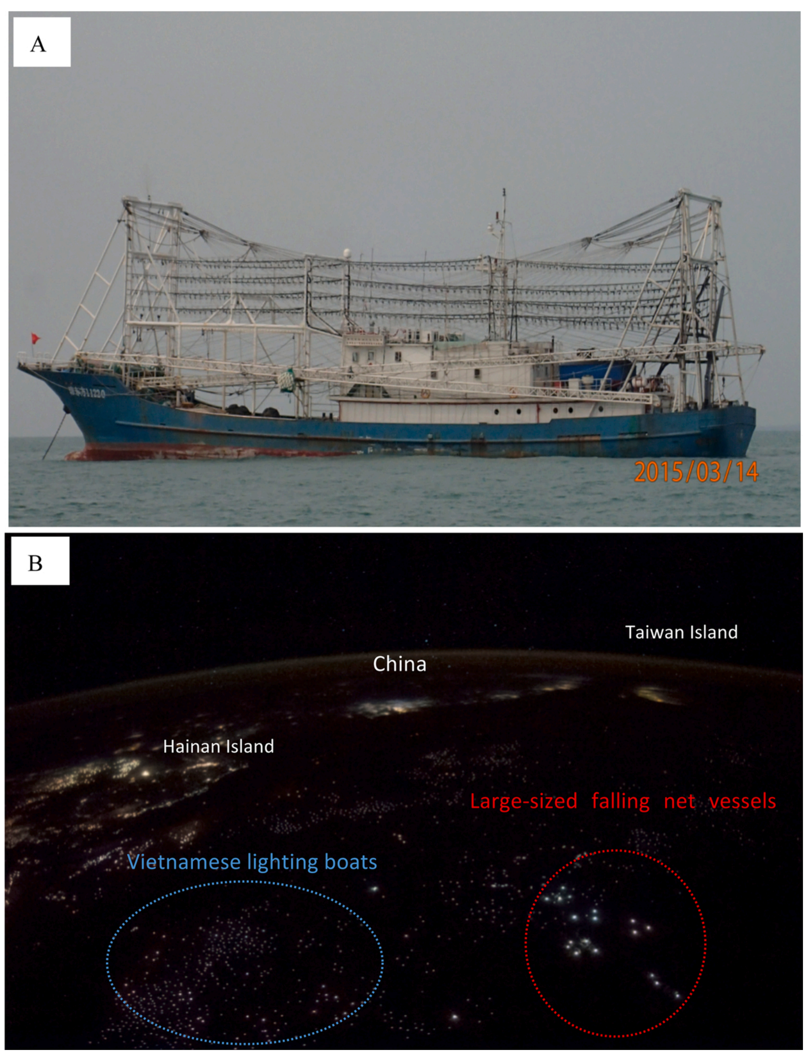

Fig. 1. A typical large-sized light falling net vessel from Hainan Province, China (A) and a photograph from the International Space Station (ISS055-E-65050) showing some extremely bright fishing lights from Chinese large-sized falling net vessels and large number of lighting boats of Vietnam in the open SCS on 10th May, 2018 (B).

by a vessel staying at fishing ground but not performing fishing due to low catch rate or other reasons, and the state of fishing means that a vessel is actively fishing in a fishing ground. We distinguished the states of activities of the studied vessel by each fishing night according to the fishing logs and compared to the states that can be inferred from VMS records and nightly satellite detections.

2.2. VMS data

Chinese VMS is now in full operation for large-sized falling net vessels. We obtained VMS data of the vessel collected by the Strategy Research Center for the SCS Fisheries from the Beidou navigation system. The dataset consisted of records for the chosen vessel during the spring fishing season of 2015. The records provide time-stamp, latitude/longitude, speed, course, and other information, and a typical gap between two vessel track records is 2 min.

2.3. Cross matching between VIIRS DNB and VMS data

In this study, we used the Visible Infrared Imaging Radiometer Suite (VIIRS) Sensor carried by the Suomi NPP as nightly satellite data source (Day/Night Band, DNB). An auto-algorithms (VBD) has been established to extract fishing-vessel-emitted lights from the VIIRS DNB and to associate them with other useful parameters, such as satellite pass time and satellite viewing zenith angle (Elvidge et al., 2015; Zhizhin et al., 2017). We used this method to obtain the radiance and associating information of light fishing boats in the SCS.

A methodology has also been proposed for cross matching VIIRS VBD with VMS tracks (Hsu et al., 2019). We adopted this methodology to obtain nightly satellite characteristics of a typical large-sized light fishing vessel. The threshold for matching a VMS record to VBD was set to be within 1 km and 1 h, i.e., if the VBD was found within 1 km of the VMS-recorded location, we treated the VBD as being from our studied vessel. Additionally, brightness temperature of M12 band was obtained from the CLASS website (http://www.bou.class.noaa.gov) to assess the weather condition, and we associated the data with the vessel's positions determined from VMS and the nightly satellite.

3. Results and discussion

3.1. Vessel state determination

According to the fishing logs, the vessel conducted two cruises in the open SCS in 2015, with most of the fishing days occurring in the spring fishing season. Based on the classification of states of activities, the vessel operated fishing for 57 days in the 3-month fishing season, took 10 days moving between fishing grounds and its home port, drifted for 12 days in the fishing grounds, and landed for 5 days in its home port between the two cruises. The purpleback flying squid, the vessel's major fishing target, exhibits strong phototropism and can be easily attracted by luring lights, but moonlight is one of the important factors hampering catch rates for this species (Yan et al., 2015). Fishermen have long perceived lunar periodicity of the squid's catch rates and always avoid fishing during the full-moon phase (Otubusin, 1990; Lowry et al., 2007; Ortegagarcia et al., 2008). Fig. 2 shows states of the vessel's activities versus moon calendar, which indicated that states of drifting, moving, and landing mainly occurred on and around the full-moon phase, while fishing took place during the waning moon, consistent with the habit of fishermen.

We also analyzed the vessel's states jointly by VMS records and corresponding nightly satellite data. The landing state that the vessel stayed at the port or by a coral reef was determined by the topography and the vessel's zero speed, while the moving state of the vessel can be assured by a higher velocity of 3–8 knots. These two states can be readily determined from the VMS records. However, both fishing and drifting states occurred in the fishing grounds with water depth of >200 m and

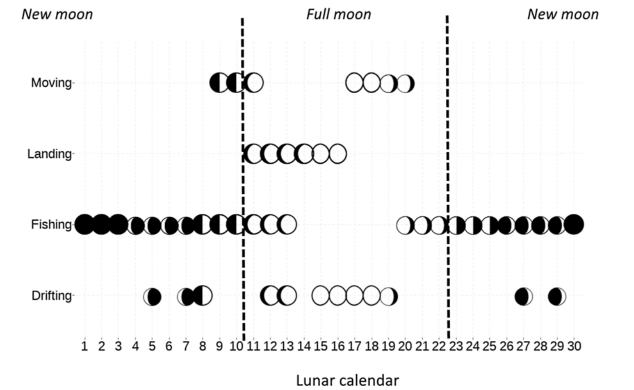

Fig. 2. States of activities of the large-sized light falling net vessel for the 3-month fishing season based on its fishing logs.

with a lower vessel velocity of <2 knots, which were difficult to differentiate with VMS records only, but could be distinguished by the radiance of lighted lamps at night.

A large-sized light falling net vessel performing fishing are lighted with ~250–500 bright lamps, which can be used as a criterion to differentiate the state of fishing from that of drifting. Although a moving or drifting vessel at night is also lighted with certain lamps, the light is too dim to be detected by a nightly satellite. Fig. 3 shows the radiance of the vessel when nightly satellite images and VMS records matched. The result indicated that during the fishing season, the nightly satellite detected the vessel for 56 times and, according to the fishing logs, all of them were in the state of fishing, with only for 1 time (1.8 %) the vessel being in the state of fishing, but not being detected by the nightly satellite. As for the states of moving and drifting determined by VMS records, none of them could be detected with nightly satellite images. The result also indicated that, although lighted with similar numbers of lamps during fishing, the radiance varied greatly, ranging from 1.34–1869.43 $nWcm^{-2}\ sr^{-1}$, with an average of 428.3 $nWcm^{-2}\ sr^{-1}$ and mostly (~90 %) higher than 50 $nWcm^{-2}\ sr^{-1}$.

Additionally, we try to explain the reasons why at one fishing night the vessel was not detected by the nightly satellite and at some fishing nights the vessel was detected with very low radiance (< 25 $nWcm^{-2}\ sr^{-1}$). It takes just a little moment for the satellite to pass over the fishing vessel and there is a gap of 10–15 min between two fishing hauls when all or most of the luring lamps are turned off and the nightly satellite may pass over just at the moment, resulting in a fishing vessel being overlooked or being detected with a low radiance.

3.2. Relation of lights to catches

Catches of the vessel were mainly composed of the purpleback flying squid and bonitos *Auxis* spp., consistent with those reported by the

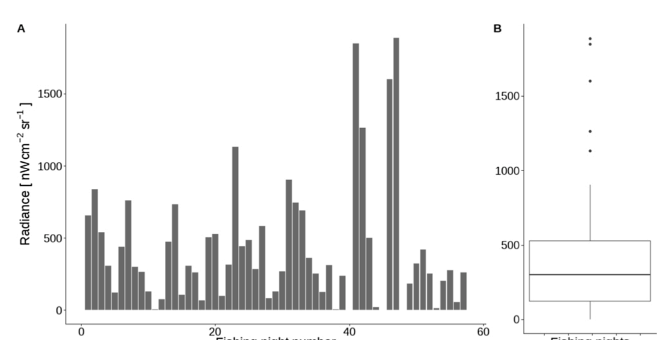

Fig. 3. Detected radiance of the large-sized light falling net vessel by fishing days (A), and boxplot of the radiance (B).

previous studies (Zhang et al., 2013; Zou et al., 2014; Yu et al., 2019a, Yu et al. 2019b). The bonito species included *Auxis thazard*, *A. rochei*, *Katsuwonus pelamis*, and *Euthynnus affinis*. Total catch by the vessel during the entire fishing season of 2015 amounted to 233.7 tons, of which the purpleback flying squid took up 83.6 %, bonitos 10.0 %, and others species 6.4 %.

Lighted lamps constitute a major cost of fishing. During the start of fishing, fishermen always use a larger number of lamps to lure squids. If catch rate is low, they will reduce the number of lights (to 200–250) or turn off all the lights and drift the vessel waiting for the next night. Fig. 4 shows passing time of the nightly satellite (Suomi-NPP) over the vessel's fishing ground. The satellite passed over the fishing ground at 1:00–3:00 am local time, when the vessel was routinely conducting its sixth or seventh fishing haul. Hence, the number of the fishing vessel's lighted lamps when the satellite passed might provide important information on its catch rate.

During the 57 fishing nights, the vessel performed a total number of 474 fishing hauls, with an average of 8.3 hauls per night. Plots of the squid catches (Fig. 4A) and total catches per night (Fig. 4B) versus numbers of fishing hauls per night showed highly significant positive correlations ($r^2 > 0.4$, both $p < 0.01$). Catches of the squid varied between 40–12840 kg/night, with an average of 3225 kg/night. Consistent with the fishing habit, the numbers of fishing hauls were usually <5 per night when squid catches were <700 kg and squid catch rates were <140 kg/haul, because of fishing cost. The prime cost for a fishing night with 10 fishing hauls and 300 lighted lamps was ~CNY16,000, while the first-hand price for the squid was ~CNY10/kg, i.e., the vessel would make profit when the catch of squids exceeded 1600 kg/night (or 160 kg/haul). This explains the reason why lower number of fishing hauls (e.g., <5 hauls) were associated with lower catches and catch rates. The plots infer that the number of fishing hauls per night or length of lighting generally increase with catches and the nightly satellite tend to detect high-catch-rate fishing vessels. It is further inferred that spatial-temporal pattern of lighting detected by the nightly satellite could indicate that of catches of the target species.

We also analyzed the relation of the vessel's catch rates to numbers of lighted lamps when the satellite passed (Fig. 5). The result showed that catch rates were significantly higher ($p < 0.001$) when a larger number of lamps were lighted, inferring that the radiance detected by the passing satellite may also be used as an indicator of catch rates.

3.3. *Factors influencing detected radiance*

Cloud condition has been recognized as an important factor influencing the detection of radiance of lighting; clouds can reduce the radiance or even totally block the observation of lights. Night-time lights have been widely used by economists and social scientists, who mainly concern about stable lights on land (Zhao et al., 2018, 2019). To remove

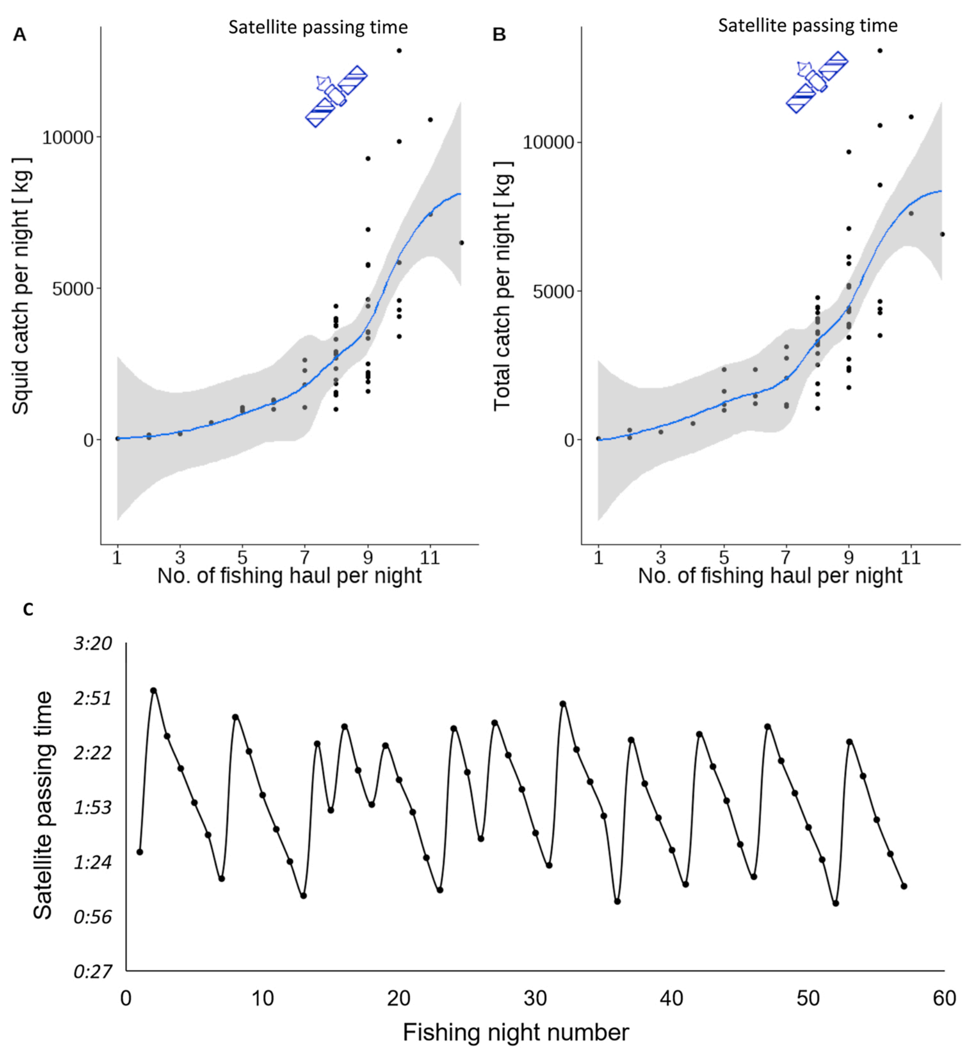

Fig. 4. Plots of squid catch (A) and total catch (B) versus number of fishing hauls per night for the vessel (both $p < 0.01$), and local time when the satellite passed over the vessel's fishing ground (C).

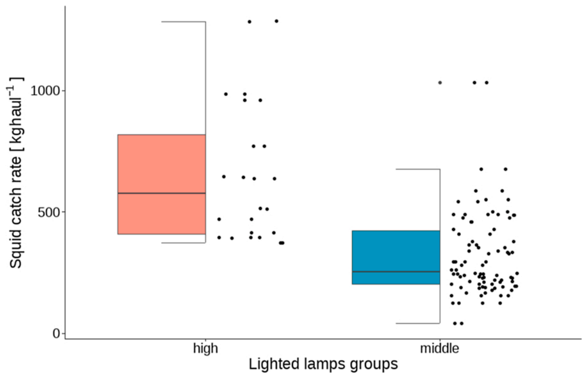

Fig. 5. The vessel's squid catch rates under different numbers of lighted lamps when the satellite passed ("middle" denotes ~250 lighted lamps and "high" denotes 400-500 lighted lamps, which were recorded by the fishing logs).

the influence of clouds, cloud-free products of night lights were used for their studies, while data collected under cloud-cover conditions can be totally omitted (Zhao et al., 2019). Unlike the on-land studies, the objects in our study are lights from fishing vessels and we concern about both spatial and temporal patterns of the lights. VBD could produce detection of light fishing vessels even in the presence of certain cloud cover (Hsu et al., 2019). Hence, it is essential to consider a broad range of weather conditions with and without cloud. Over warm waters of the study area, clouds are colder than the underlying ocean surface and will have lower brightness temperature in the M12 imagery. Compared to thin clouds, thick clouds will decrease the temperature to a larger degree. In this study, the M12 brightness temperature of matched vessel maintained at high values (>289 K) during the whole fishing season, which indicated low cloud fraction/cover in the open-SCS fishing ground. This may also explain high match rate (98.2 %) for the fishing vessel between VMS and VBD, which is much higher than those for other reported lighting fishing crafts (Hsu et al., 2019).

The swath width of VIIRS is up to 3000 km, which results in a wide span of satellite VZA. In addition to clouds, anisotropic characteristics has been reported as another important factor influencing the VIIRS DNB radiance detection (Coesfeld et al., 2018; Li et al., 2019). After removing the fishing gap induced low radiance with lower illuminated coverage, 50 fishing nights left (Fig. S2, Table 1). Our analysis showed that the VZA significantly influences the detected radiance from the vessel, with higher VZA corresponding to higher detected radiance ($r^2 = 0.27$, $p < 0.001$; Fig. 6). The reason for this phenomenon may be that lighting of this type of vessels is mostly directed towards the sides instead of to the sky. This finding also suggests that removing the angular effect would be important for inferring the number of lighted lamps and fishing catch rate.

Finally, we further removed potential cloud-affected fishing nights (M12 brightness temperature < 296.4 K), and sorted the fishing nights into two groups based on numbers of lighted lamps to investigate the relation of radiance to VZA. The results show that higher values of detected radiance are generally associated with larger numbers of lighted lamps (Fig.7), and the coefficient of correlation between detected radiance and tangent (VZA) increases to $r^2 = 0.59$ ($p < 0.001$) for middle group, and to $r^2 = 0.84$ ($p < 0.001$) for high group. In the present analysis, the two lighting states (high and groups) can be distinguished only under high VZA conditions and it is difficult to derive a clear relation of radiance to lighting and VZA for this type of vessels because of small sample size. However, the analysis indicated that night light detections may still provide a reasonable proxy for catch given the relationship between radiance and catch rates if VZA and weather conditions are accounted for. Another nightly satellite (JPSS1) with VIIRS has been launched in 2017, crossing the equator approximately 50 min prior to the Suomi NPP, at approximately 12:40 PM (ascending node) and 12:40 AM (descending node) (Oudrari et al., 2015). In the

Table 1
Numbers of lighted lamps recorded by fishing log, radiance, satellite viewing zenith angle (VZA), and M12 brightness temperature (BT) for the large-sized fall net vessel.

Night no.	No. of lighted lamps	Radiance (nWcm^{-2} sr^{-1})	VZA (°)	M12 BT (K)
1	250	655.0	45.3	298.1
2	250	836.4	69.1	295.1
3	250	538.5	56.3	296.7
4	250	305.7	34.1	293.9
5	250	122.4	1.8	295.7
6	250	437.7	36.8	298.3
7	250	758.7	58.1	297.2
8	250	298.3	61.3	296.2
9	250	263.2	43.0	298.0
10	250	128.4	10.8	297.2
11	250	73.4	52.3	297.5
12	250	475.3	66.9	290.5
13	250	732.7	50.1	297.7
14	250	104.3	15.4	298.4
15	250	308.9	55.7	295.8
16	250	262.0	32.9	297.1
17	250	67.8	3.8	297.2
18	250	506.3	49.9	297.7
19	400	527.6	22.6	298.5
20	250	99.8	15.6	299.1
21	300	314.6	45.6	297.7
22	270	1133.7	63.1	296.4
23	280	441.7	55.9	294.6
24	320	483.8	33.2	298.0
25	320	282.4	37.1	297.7
26	320	583.5	60.9	291.6
27	320	84.4	42.4	296.8
28	320	128.7	11.3	299.2
29	300	269.1	27.0	298.9
30	320	903.0	52.0	298.1
31	320	745.6	65.5	294.0
32	320	689.3	50.1	296.8
33	320	360.1	22.5	298.7
34	320	253.9	20.6	298.2
35	250	124.5	65.5	295.4
36	500	312.7	49.8	297.5
37	500	237.9	15.9	294.7
38	500	1849.3	63.3	296.5
39	500	1264.9	55.8	298.2
40	500	502.0	33.1	300.1
41	500	1601.7	56.6	296.8
42	500	1887.7	62.9	297.5
43	500	185.5	14.8	299.1
44	500	323.0	23.7	298.1
45	500	420.6	50.5	294.4
46	250	253.2	66.0	289.8
47	250	13.7	52.2	295.8
48	250	202.2	26.8	292.5
49	250	277.4	10.9	299.2
50	250	57.2	43.0	296.3

future study, we can have images from the both nightly satellites, which will decrease the probability of missing a fishing vessel because of the gap between two fishing hauls and significantly improve the monitoring performance of this type of vessels.

4. Conclusion

Due to increasing interests in the oceanic fishery resources in the open SCS, it is necessary to monitor and manage the fishery for the dominant purpleback flying squid. Our analysis indicated that the nightly satellite, although passing over just for a little moment, can detect most of the large-sized falling net vessels conducting light fishing, and a combination of VMS and nightly satellite records performs well in locating the positions and identifying fishing activities for this type of vessels. Comparisons of fishing logs with nightly satellite records also indicated that numbers of lighted lamps on the vessel well correlated with its catch rates, which means that a high-catch area could be

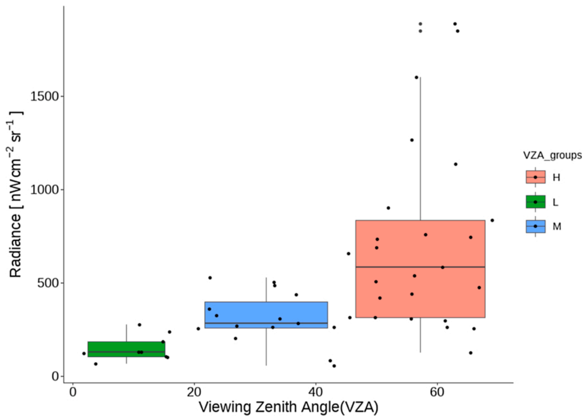

Fig. 6. Scatter plot of the vessel's detected radiance versus satellite VZA and box-plot of the radiance with varied VZA ranges. L for VZA <20 °, M for 20°< VZA <45 °, and H for VZA >45 °.

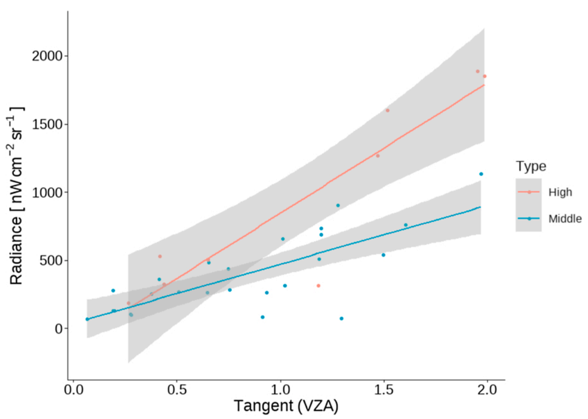

Fig. 7. Correlation between DNB radiance from the large-sized falling-net vessel and tangent (VZA) ("Middle" denotes ~250 lighted lamps and "High" denotes 400-500 lighted lamps).

inferred from the detected radiance from the fishing fleet after corrected for the effects of satellite VZA and cloud conditions. Furthermore, a better forecast for fishing grounds would come into being in the future based on monitoring the fishing vessels jointly with VMS and nightly satellite.

CRediT authorship contribution statement

Jiajun Li: Conceptualization, Funding acquisition, Methodology, Investigation, Formal analysis, Writing - review & editing. **Peng Zhang**: Conceptualization, Investigation, Resources. **Yancong Cai**: Investigation, Data curation, Formal analysis, Writing - original draft. **Qingling Zhang**: Conceptualization, Writing - Original Draft, Resources. **Kui Zhang**: Writing - review & editing. **Zhiyou Jing:** Conceptualization, Writing - review & editing. **Qiaer Wu:** Funding acquisition, Resources. **Yongsong Qiu:** Conceptualization, Data curation, Formal analysis, Writing - review & editing. **Shengwei Ma:** Funding acquisition, Resources. **Zuozhi Chen:** Conceptualization, Funding acquisition, Resources.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fishres.2021.106100.

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