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Reliable estimation of IUU fishing catch amounts in the northwestern Pacific adjacent to the Japanese EEZ: Potential for usage of satellite remote sensing images

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ABSTRACT

To establish an estimation procedure for reliable catch amount of illegal, unreported and unregulated (IUU) fishing, light-gathering fishing operations in the northwestern Pacific were analyzed based on the Visible Infrared Imaging Radiometer Suite (VIIRS) day/night band (DNB) data provided by the Suomi National Polar Partnership (SNPP) satellite. The estimated fishing activities were compared with the navigation tracks of vessels obtained from the automatic identification system (AIS). As a model case, the fishing activities of Chinese fishing boats using fish aggregation lights outside the Japanese EEZ in the northwestern Pacific were analyzed from mid-June to early-September 2016. Integration analyses of VIIRS DNB data and AIS information provided reliable data for estimating the fishing activities of Chinese fishing boats and suggested the importance of estimating fish carrier ship movements. The total amount of the chub mackerel (*Scomber japonicus*) catch during this period was independently estimated from three angles: 1) the fishing capacity of the fishing boats, 2) the freezing capacity of refrigeration factory ships and 3) the fish hold capacity of the fish carrier ships, based on information obtained from interviews with Chinese fisheries companies. These estimates indicated that the total amount of mackerel catch by Chinese fisheries was more than 80% of the allowable biological catch (ABC) of Japan in this area in 2016. This suggests that Pacific high seas fishing has a significant impact on the future of fish abundance. Our proposed procedure raises the possibility of evaluating the fishing impact of some forms of IUU fisheries independently from conventional statistical reports.

1. Introduction

The threat of illegal, unreported and unregulated (IUU) fishing to marine living resources is receiving a great deal of attention in many international fora, such as the United Nations' Sustainable Development Goals [33] and various studies [1,29]. IUU fishing is not a new issue: it has been observed both within EEZs and on the high seas for at least the past three decades. Even though great efforts have been expended at the national, bilateral, multilateral and global levels to halt IUU fishing, the threat continues to grow [27]. This could result in unreliable assessments of fish stocks and ineffective fisheries management if IUU fisheries continue [11]. The FAO and intergovernmental organizations have repeatedly issued warnings against IUU fisheries since the early 1990s [9,34]. It has been emphasized that IUU fishing can damage vulnerable fish stocks and/or fish stocks still recovering from serious overexploitation [2]. In response, the FAO developed the "International Plan of Action to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing (IPOA-IUU)" [10]. Then the FAO promoted the establishment of the Port State Measures international agreement as an effective tool for eliminating IUU fisheries [12,30]. However, these actions have yet to produce the intended outcome, *i.e.*, of containing IUU fishing. Instead the catch amount of IUU fisheries seems to be increasing, and IUU fisheries appear to be expanding to other areas in different forms [27].

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The expansion of IUU fisheries has been observed in the high seas areas of the northwestern Pacific recently. Chinese Taipei fishing vessels increased their catch of Pacific saury, *Cololabis saira*, from 27,900 metric tonnes (MT) (2000) to 165,700 MT (2010) in the 2000s in this region, while almost no substantial fishing activities had previously been conducted [32]. Following this expansion of Chinese Taipei's fishing, the People's Republic of China (here referred to as 'China', and excluding Taiwan, Hong Kong and Macau) joined the fishing there in 2012. However, the Chinese fishing fleets did not remain solely in saury fishing, but expanded to other pelagic fisheries. In the last few years, Chinese tiger-net and stick-held dip net fishing boats have been increasingly sighted on the high seas in this region. In 2016, Japanese Fisheries Agency (JFA) patrol vessels recorded more than 200 Chinese boats [15]. The types of fishing gear using fish aggregation lights are like purse seines but are much more efficient in catching all kinds of fish, such as sardine, mackerel, squid, saury, and juveniles of many species in the pelagic water of the fishing grounds. According to the North Pacific Fisheries Commission (NPFC), a newly established RFMO responsible for fisheries in this region, the Chinese catch of chub mackerel, *Scomber japonicus*, which is the most expensive and thus assumed to be the main target species, increased markedly from 24,629 MT by 20 fishing boats in 2014 to 142,994 MT by 89 fishing boats in 2016 [16]. However, false identification of vessels is frequently recorded in photos taken by Japanese patrol vessels. These cases include (1) multiple Chinese boats displaying the same name and registration number, and (2) boats displaying a different vessel name on each side of their hull [15]. As a result, the number of fishing boats and the amount of catch are likely to be considerably under-reported.

The NPFC established the "Conservation and management measure on information requirements for vessel registration" on 3 September 2015 [22]. The agreement adopted at the same meeting indicated that unlisted fishing vessels operating in this region should be recognized as IUU fishing boats [23]. Catch amount should be reported to the NPFC until the end of February and fishing fleets that did not record or report their catch are recognized as IUU fishing [23]. According to the observation at sea by the Japanese patrol and research vessels, it is unquestionable that a significant number of false identification vessels, *i.e.*, IUU vessels, are operating in this region in addition to the duly licensed Chinese fishing boats. NPFC adopted resolutions in 2015 and 2016 calling for self-restrictions of each member upon further increase of fishing vessels fishing for Pacific saury and chub mackerel [21,24]. While the Chinese government appears to have made efforts to contain the increase in fishing vessels, it seems that a significant number of unlicensed Chinese fishing vessels have started fishing in this region. Thus, the reported catch data cannot be solely relied upon, and it is crucial to find a way to assess actual fishing effort and catch, including IUU fishing, in the relevant stock assessments. Otherwise, fishing impacts upon the stocks would be underestimated and the assessment would result in an unreasonably optimistic future of the stocks. Fortunately, the recent introduction of new satellite technologies and other useful information-monitoring systems has enhanced our abilities to assess IUU activities and their impact on marine resources even in high seas area.

The Suomi National Polar Partnership (SNPP) satellite, carrying sensors for illuminated intensity, was launched in 2011 for global observation of the Earth. It enabled us to obtain more reliable and precise information on the activities of fishing boats that use fish aggregation lights. The real-time observation of brightly-lit fishing boats was reported as early as the 1970s [5,6]. This satellite is equipped with the Visible Infrared Imaging Radiometer Suite (VIIRS) as its primary image sensor. The VIIRS day/night band (DNB) collects even low light image data with high horizontal spatial resolution of down to approx. 0.75 km × 0.75 km [7,18,19]. Increased data volume with high resolution and the lower detection limit in radiance has created a new operational field to monitor the activities of dimly-lit fishing boats and process algorithms for eliminating several types of noise [8].

Another information source has become available recently. Automatic identification systems (AIS) were made a requirement for international cruising vessels with a gross tonnage of 300 t or more by the International Convention for the Safety of Life at Sea (SOLAS) in 2002. AIS started as a coastal communication tool. Later, a satellite AIS network was established after the STS-129 space shuttle mission in 2009, during which shipboard AIS signals using the VHF band were observed to reach up to 400 km vertically, although the AIS has a horizontal range limit of only 40 nautical miles (74 km). ORBCOMM currently operates the AIS network service (http://www.orbcomm.com/en/industries/maritime/satellite-ais, downloaded on Sept. 23rd, 2016) and information service companies provide analysis of AIS information *via* the internet (Shipfinder: http://shipfinder.co/, Marinetraffic; http://www.marinetraffic.com/, downloaded on Sept. 23rd, 2016). These information systems are useful data sources for current scientific analyses [28]. However, several problems related to the operation of AIS have been reported, *e.g.*, deliberate suspension of signal transmissions from the onboard AIS, low reliability of AIS signals, including incorrect datum setting and the security vulnerability of AIS itself [13]. In spite of these particular drawbacks, AIS is still a powerful tool for monitoring the activities of target vessels because of the huge amount of AIS data being accumulated on a close to real-time basis.

The Chinese fishing boats in the northwestern Pacific operate at night and use fish aggregation lights. Thus, the above two new information sources can be used to analyze their movements. VIIRS DNB data provide the information on fishing operations at night, while AIS simultaneously reports the ship's name, size, location, speed and heading. In the present study, seasonal changes in patterns of fish aggregation lights were first described on the high seas area of the northwestern Pacific from May 2013 to September 2016. Then, the nightly distribution of fishing boats analyzed using the VIIRS DNB data was compared with the navigation records reported from the AIS, with the support of observation reports from Japanese fishery patrol vessels, during a period from the middle of June to early September 2016. To estimate the total amount of catch, several Chinese refrigeration factory ships and fish carrier ships were tracked using AIS information as examples. Information on fishing activities was also obtained during interviews with fisheries companies and vessel-building industries in China. Catch amounts made in the target area were estimated based on these data, the information on the fishing capacity of fishing boats from the NPFC vessel data, [25] and by holding interviews. Our proposed procedure opens the potential for evaluating the fishing impact of IUU fisheries independently from the conventional reported catch data.

2. Materials and methods

2.1. VIIRS DNB information

Real-time data from the Suomi National Polar-orbiting Partnership (SNPP), operated by NOAA, were downloaded from Wisconsin State University's ftp site, in addition to the archived data since 2013 (ftp://snpp.ssec.wisc.edu/ingest/viirs/npp/, downloaded daily). Visible Infrared Imaging Radiometer Suite (VIIRS) Day-Night Band (DNB) data and cloud masking (CM) data were included in the daily obtained data set (Fig. 1). Pixels indicating local maximum values of radiance were first extracted by comparison with the surrounding radiance values from the dataset of DNB (Figs. 1, 2A).

Various error sources in the DNB data, including the reflections of sun, moon and starlight reflected by clouds and other types of noise, were eliminated step-by-step (Fig. 1). The effect of sunlight was first eliminated according to the value of SZA during two months around the summer solstice north of 40°N. Then, the possible lights from fishing boats were selected, taking into account the effects of cloud and the moon (Fig. 1, Fig. 2B). At the same time, the halo noise around the light points of fishing boats, which was observed when the light passed

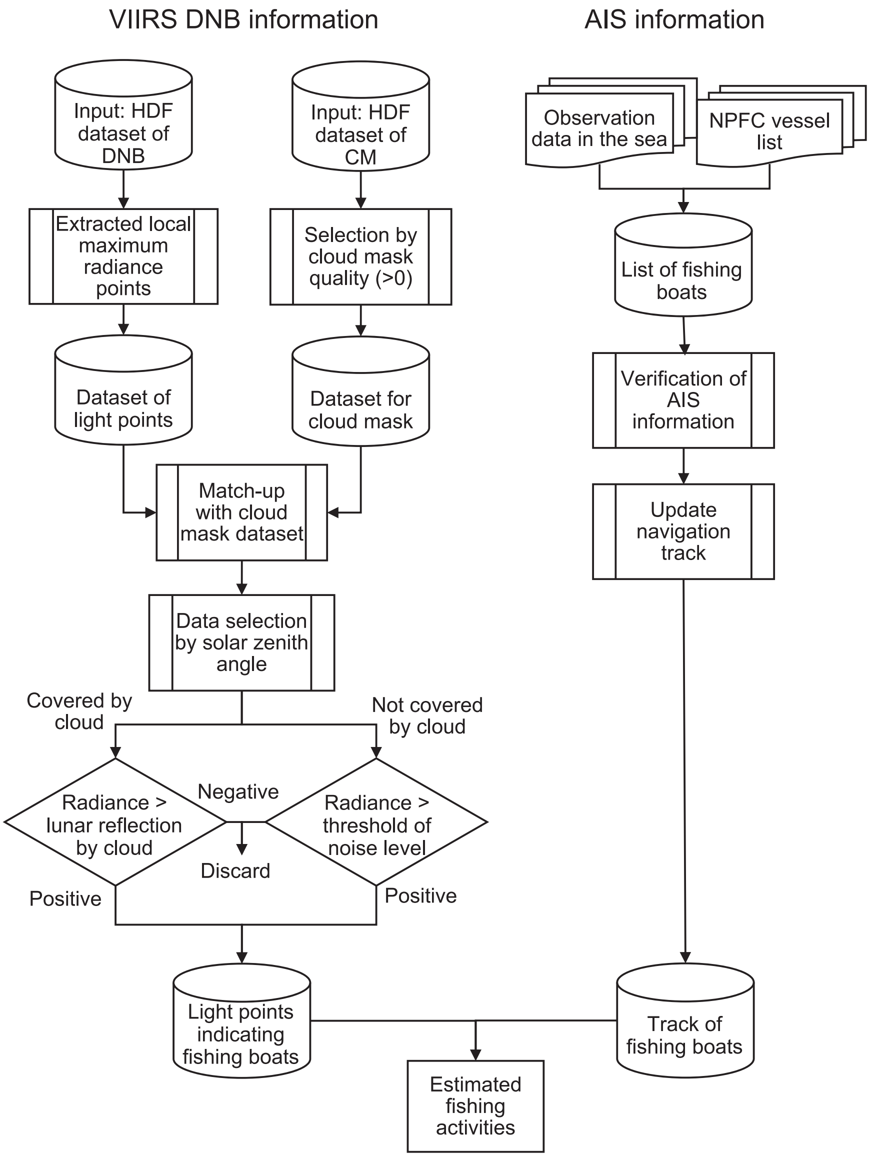

Fig. 1. Schematic diagram of the processes of data analysis showing a comparison between the VIIRS DNB and AIS information.

through the cloud, was eliminated by the difference between the radiance of the target pixel and the comparison radiance 20–30 km away from the target pixel. The finalized light point dataset was used for counting the number of fishing boats (Fig. 2D). The number of light points of fishing vessels was counted for comparison with the tracks of fishing vessels estimated from the AIS analyses mentioned below. Small blocks for calculating lit fishing boats were set following the information of AIS analyses (Fig. 2D). Further details on the analyses of VIIRS-DNB can be found in Supplementary material.

2.2. AIS information

A list of Chinese fishing vessels operating in the northwestern Pacific was compiled from several data sources, including Chinese NPFC vessel lists [25], *in situ* observation reports from Japanese fishery patrol vessels that were provided from JFA simply for checking vessel names, and fisheries research vessels (Fig. 1). Navigation track information of fishing boats on the list were obtained from Automatic Identification System (AIS) information from the Shipfinder services provided by TST Corporation in Japan (http://www.toyoshingo.co.jp/site/portal/en/index.html, downloaded daily). Verification of AIS information, including ship name, ship size and location, were conducted by cross-checking with the observation reports. The navigation tracks of all fishing vessels in the list were compiled every week by compiling the most recent AIS information obtained from Shipfinder. The navigation track datasets needed to be updated due to the deliberate suspension of their signal transmission from the onboard AIS transponder, as mentioned in the Results.

2.3. Fishing activities

Fishing activities were described by making a comparison between the dataset of light points of fishing boats from the results of VIIRS DNB and the dataset of navigation tracks of fishing boats provided by the AIS. Three groups composed of vessels from different flag nations were observed at the beginning of the navigation track analyses and were continuously monitored to identify which fishing grounds they visited (see Results, Table 1, Fig. 4B). Thus, the fishing boats observed in the results of VIIRS DNB were also separated into three groups, in the same way as when following the results of AIS analyses. Several refrigeration factory ships and fish carrier ships were found in the northwestern Pacific from the observation reports, NPFC list [25] and the AIS analyses. The navigation tracks of these vessels were carefully monitored, because this information was used for the estimation of catch amounts. Also, these vessels did not use lights at night and so were not recorded in the dataset of light points of fishing vessels.

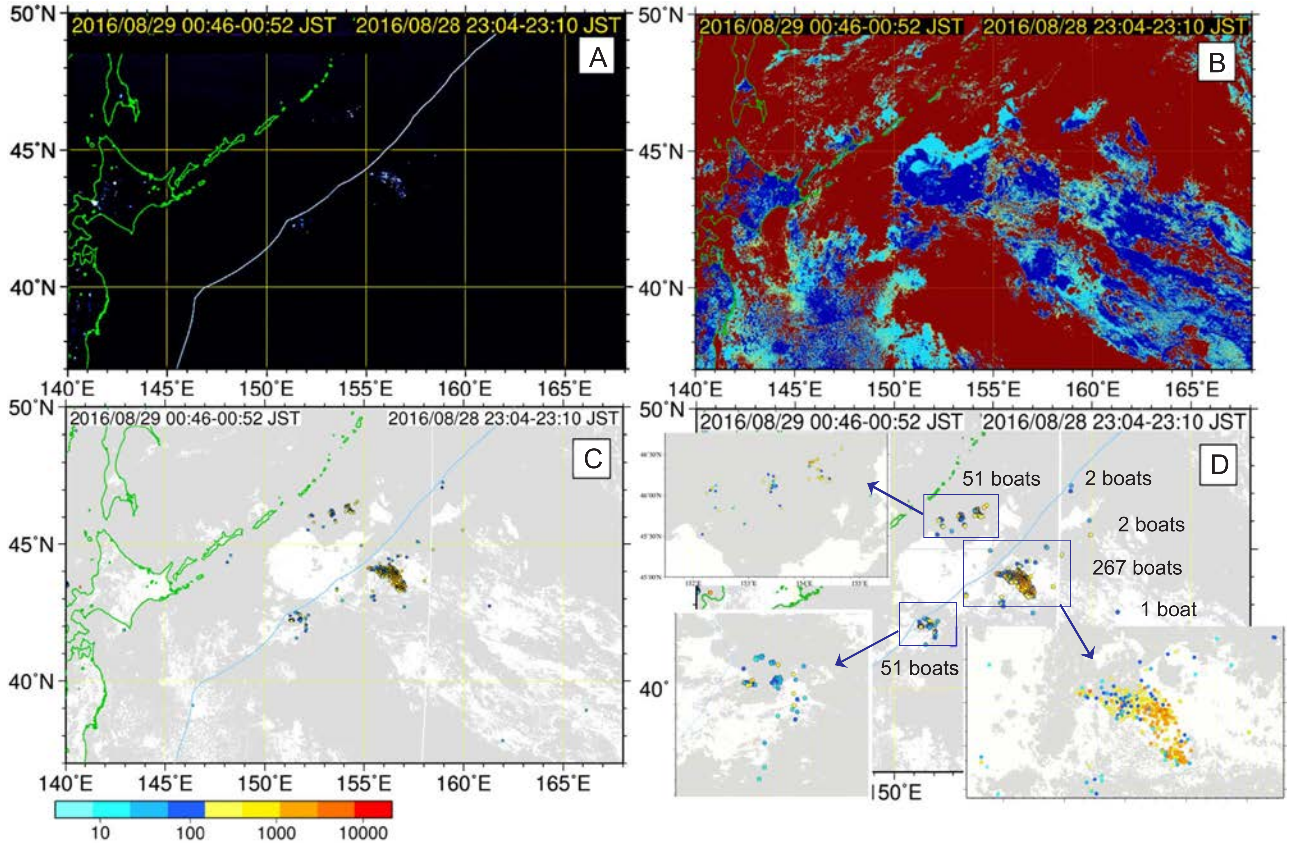

Fig. 2. Example of processing images of VIIRS DNB data in the northwestern Pacific obtained from two satellite orbits on August 28th and 29th, 2016 (A: local maximum radiances in DNB image; B: cloud data in CM image; C: extracted radiance image; D: counting of radiance points using local moon and cloud threshold values (see Supplementary material)). In the CM image (Panel B), red, yellow, light blue and blue pixels indicate confidently cloudy, probably cloudy, probably clear and confidently clear, respectively. The color chart indicates the relative value of radiance in $\times 10^{-10}$ W cm^{-2} sr^{-1} in the extracted radiance image (Panels C and D).

2.4. Information acquired for fishing catch estimation

Interviews on fishing from tiger-net fishing boats were conducted in mainland China during exchange programs between the China Ocean Fisheries Association and the Japan Purse Seiners' Association at several fishing companies and shipbuilders. Interviews were conducted five times at several Chinese companies from 2012 to 2016. They took place in Xiamen (Fujian) to Dalian (Liaoning), including the large fishing ports of Taizhou and Zhoushan (Zhejiang) and Fuzhou (Fujian). Information on fishing activities was obtained at interviews concerning

Table 1

Comparison of the number of fishing vessels between the results of VIIRS DNB and AIS outside the Japanese and Russian EEZ during the summer season of 2016. Values of VIIRS DNB and AIS are indicated on the corresponding analyzing dates. Overlap of the date in AIS columns did not mean double counts for the same ships. MIF means moon-illuminated fraction (%) which reaches a maximum (100%) at full moon. Groups A - C in the data for VIIRS DNB corresponded to the original area group during June 27th to July 6th shown in Fig. 4B. Vessels belonging to the original groups were followed using the AIS data. Corresponding lit fishing vessels were then counted in the same area for AIS in the data of VIIRS DNB. Two capital letters indicate the flag nations of fishing vessels (CH: China, TW: Taiwan, KR: Korea, RU: Russia). Distributions of fishing vessels of the date with an asterisk are shown in Fig. 4.

VIIRS DNB							AIS							
								Number of vessels						
Date	Lunar age	MIF (%)	Number of vessels				Date	A	B				C	total
			A	B	C	total		CH	CH	TW	KR	RU	CH	
Jun 19th – Jun 20th	14.0	99.1	17	32	–	49	Jun 14th – Jun 21st	34	3	22	8	3	0	70
Jun 28th	22.0	50.7	69	29	–	98	Jun 21st – Jun 29th	39	3	27	10	4	1	84
Jul 4th – Jul 5th*	29.0	0.3	23	60	16	99	Jun 27th – Jul 6th*	41	8	50	11	4	53	167
Jul 10th – Jul 11th	5.7	36.5	57	53	3	113	Jul 5th – Jul 13th	41	13	57	10	3	66	190
Jul 18th – Jul 19th*	13.7	97.7	48	28	22	98	Jul 11th – Jul 20th*	46	17	61	11	4	73	212
Jul 26th – Jul 27th*	21.7	54.1	49	83	60	192	Jul 19th – Jul 27th*	43	16	47	12	4	72	194
Jul 31st – Aug 1st	26.7	6.1	139^{A+C}	44	–	183								
Aug 3rd – Aug 4th	0.3	0.7	124^{A+C}	109	–	233	Jul 25th – Aug 4th	41	21	57	12	2	68	201
Aug 7th – Aug 8th*	4.3	21.6	85^{A+C}	114	–	199	Aug 3rd – Aug 9th*	25	21	64	2	1	71	184
Aug 24th – Aug 25th*	21.3	56.5	86^{A+C}	152^{B+C}	–	238	Aug 15th – Aug 25th*	34	15	58	0	1	72	180
Aug 28th – Aug 29th	25.3	14.9	53	271^{A+B+C}	–	324	Aug 23rd – Aug 30th	47	17	57	0	1	73	195
Sep 4th – Sep 5th	2.7	9.8	72	241^{B+C}	–	313	Aug 29th – Sep 7th	55	18	53	0	1	72	199

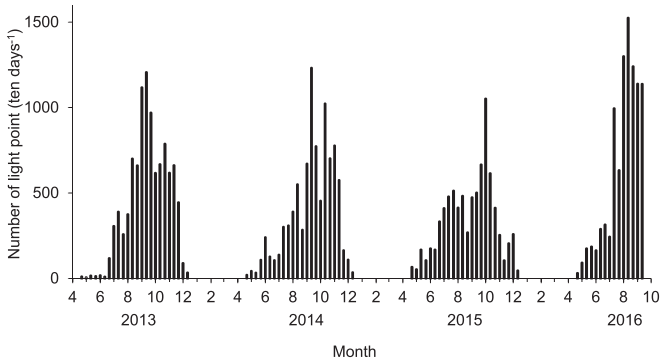

Fig. 3. Temporal change in maximum radiance points from May to October (except January to April) during 2013–2016. Number of light points indicating radiance 400 × 10^{-10} W cm^{-2} sr^{-1} greater than surrounding pixels were counted every ten days for each month. These counts of light points contained noise, including lunar reflections.

the operation of fishing boats, fishing duration, daily catch amount and number of tows at night, operations of fish carrier ships, and so on. Information from these interviews was compared with the fishing capabilities described in the NPFC vessel lists [25] and used for estimation of total catch amount.

3. Results

3.1. Seasonal changes in light points

Total numbers of light points were analyzed to elucidate the seasonal fishing activities from May 2013 to September 2016 on the high seas area of the northwestern Pacific (Fig. 3). The local maximum radiance points, indicating radiance 400 × 10^{-10} W cm^{-2} sr^{-1} larger than surrounding pixels, were counted for every ten-day period of each month. The analyzed area was 35–38°N and 141–172°E and thus fishing boats of several countries were included. Even before the noise elimination process (Fig. 1), the seasonal changes in light points clearly demonstrated the seasonal patterns of fishing activities. The number of light points increased in July and decreased in November from 2013 to 2015, whereas in 2016, the number of light points rapidly increased from mid-July and indicated the highest values from mid-August to late-September seen during the last four years.

3.2. Distribution of light points

Distribution of lit fishing boats analyzed by the VIIRS DNB data indicated good correspondence with that from the AIS data (Table 1, Fig. 4), although the accuracy of number of lit fishing boats obtained by VIIRS DNB depended on cloud conditions and lunar age (LA). The preliminary trial for checking the accuracy of AIS data from Chinese fishing boats indicated that roughly half of the boats suspended their signal transmissions from their onboard AIS transponder. One week was considered appropriate as the duration for compiling the AIS data for most of the fishing boats, since AIS information for a given day could not be acquired for a significant percentage of fishing boats. Navigation tracks shown in the AIS data indicated the presence of three fishing boat groups: Group A, distributed around 41°N 150°E, which consisted of 41 Chinese fishing boats; Group B, distributed around 41°N 160–161°E, consisting of 73 fishing boats under various flags; and Group C, distributed around 39–40°N and 160–161°E, consisting of 53 Chinese boats from June 27th to July 6th (Table 1, Fig. 4B). On the other hand, from the VIIRS DNB data, only 99 lit fishing boats were recognized under the dark moon due to the mostly cloudy conditions prevailing from July 4th–5th (Fig. 4A). The three groups of fishing boats identified from the AIS data grew in number due to continuous addition of newly-recruited fishing boats to the fishing grounds (Table 1). From July 26th–27th, fishing boat distribution, estimated from both VIIRS DNB and AIS data, indicated good correspondence (Table 1) because of clear conditions with a half-moon in the fishing grounds (Fig. 4E, F). Many fishing boats in Group A took shelter around Hokkaido, Japan, since Typhoon Omais (#5_2016), passing at 38°N 144°E on August 9th, impeded fishing operations around 145–155°E (Fig. 4G, H). VIIRS DNB data clearly indicated that on the day before the typhoon passed through, many fishing boats were operating in the offshore high seas area under a mostly clear sky with a crescent moon. The number of lit fishing boats estimated from VIIRS DNB data was greater than that from AIS after late August (Table 1, Fig. 4I, J), because the LA and brightness of the moon (MIF: moon illuminated fraction) was not very large.

AIS information was particularly useful during the full moon. Large discrepancies in the estimated numbers of fishing boats between the two methods was found on the nights of June 19th–20th and July 18th–19th, because of the high degree of lunar reflection by the clouds (Table 1, Fig. 4C, D). The effect of lunar reflection was larger under a cloudy sky with the moon, while the radiance from the light of fishing boats in a cloudless sky was still detectable using the method detailed in this study, even at full moon. As a good example of clear sky conditions, the number of lit fishing boats estimated from VIIRS DNB data turned out to be almost the same as that from AIS data at 40–42°N 150–152°E (Area A) during July 18th to 19th, even under full moon conditions (Table 1, Fig. 4C, D).

3.3. Navigation tracks of factory ships

The observation reports of fishing boats included several large refrigeration factory ships (RFS) over 60 m in length and fish carrier ships listed in the NPFC data [25]. Eight refrigeration factory ships were selected to be monitored for testing the possibility of catch amount estimation (Fig. 5). AIS signals from most of the ships were not recorded between their departure from Chinese ports and arrival in the fishing grounds except for when passing nearby Japanese channels, *e.g.,* the Tsugaru Channel. During their stays in the fishing grounds, AIS signals were not continuously available. Three of the eight ships remained more than one month outside the Japanese EEZ (Fig. 5, RFS A-C), while the other five ships shuttled between the fishing grounds and Chinese ports (Fig. 5, RFS D-H). Fifteen shuttle cruises (round trip from China to the northwestern Pacific) were identified for the five carriers during four months, although the AIS signals were fractionally recorded (Fig. 5, RFS D-H). Durations of staying in the fishing grounds were estimated based on reliable AIS records (Fig. 5, RFS D, F, H) which averaged 14.2 days per cruise. One refrigeration factory ship entered a port on Iturup Island (Fig. 5, RFS H). The navigation tracks of two fish carrier ships in the NPFC vessel list were successfully monitored (Fig. 6). One fish carrier stayed in the fishing grounds for more than three months, whereas another ship stayed only three days in the fishing grounds while cruising *via* Meynypilgyno (Russia) to China.

3.4. Estimation of catch amount

The total catch amount of chub mackerel was estimated during the summer season, lasting from June 14th to September 5th (84 days) in the Group A operating area, using several assumptions obtained from the information of the interviews at Chinese fisheries companies and from the summarized estimates from the NPFC vessel lists [25] (Table 2). The industry information obtained from Chinese fishing companies provided supporting evidence that fishing boats remained for long periods in high seas areas and that a large quantity of fish was transferred to fish carrier ships directly or *via* refrigeration factory ships. Our estimation was therefore independently conducted from three angles: 1) estimation of fishing capacity of the fishing boats, 2) freezing capacity of the refrigeration factory ships and 3) fish hold capacity of the fish carrier ships. Two types of fishing boats using fish aggregation lights were operating in the Group A operating area. The lighting purse seine (LPS) and stick-held dip net (SDN) boats targeted

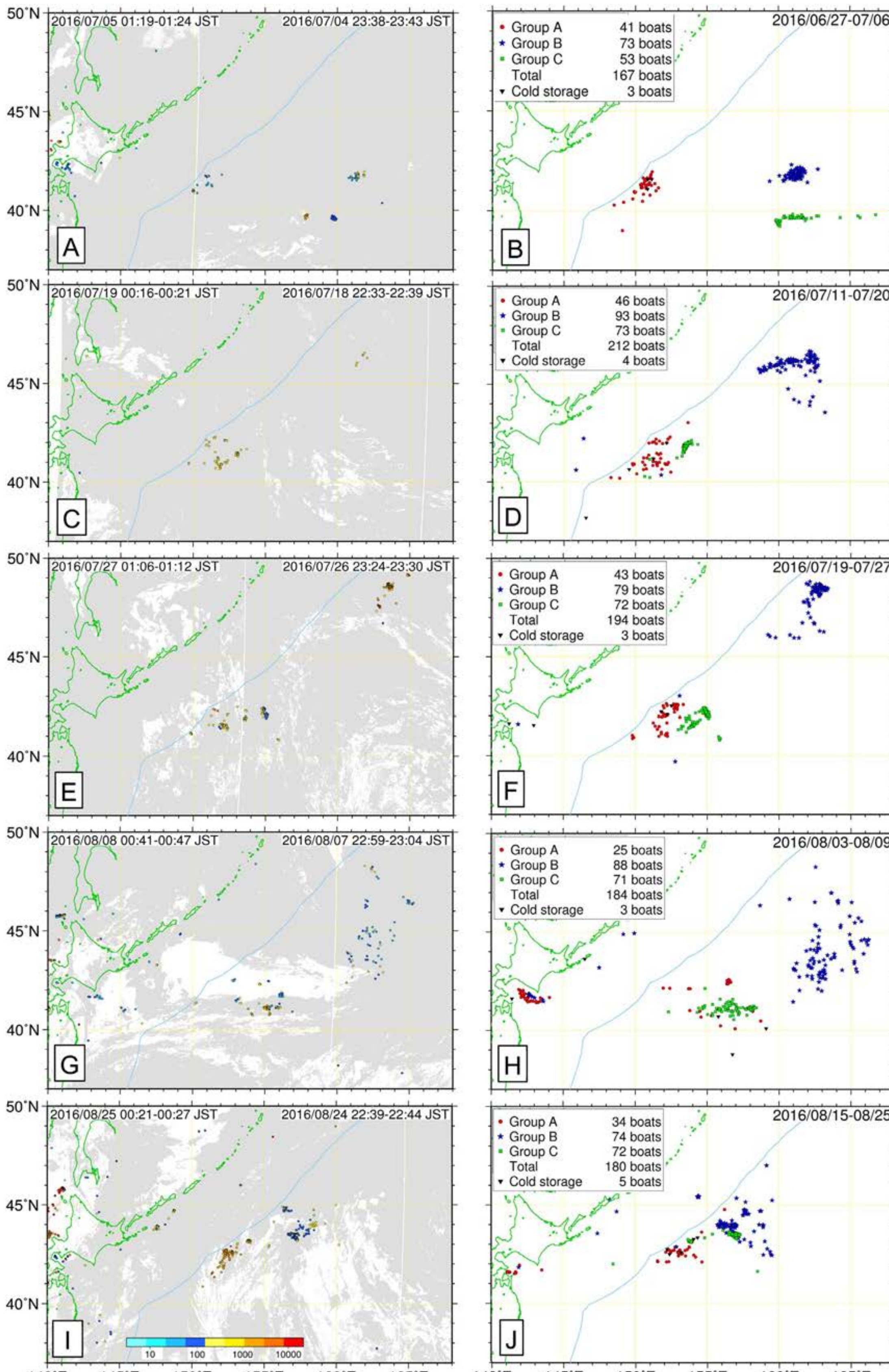

Fig. 4. Temporal changes in light point distribution from VIIRS DNB data (left panels) compared with those of the locations of fishing vessels estimated from AIS information on the corresponding date (right panels) during the summer season in 2016 (A & B: July 5th; C & D: July 19th; E & F: July 27th; G & H: August 8th; I & J: August 25th). These panels correspond to the data shown in Table 1. The color chart indicates the relative values of radiance in $\times 10^{-10}$ W cm^{-2} sr^{-1} in the left panels. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

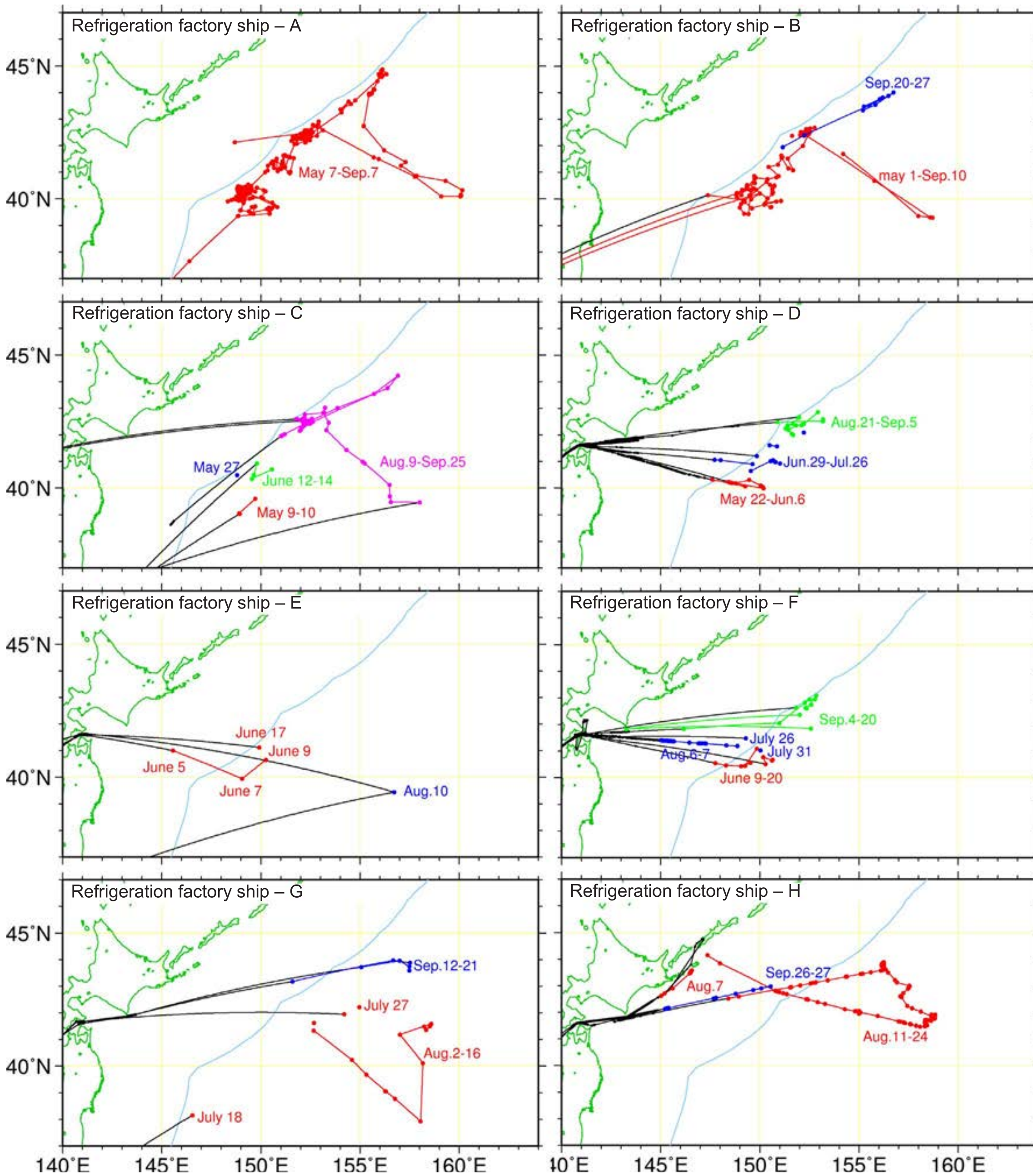

Fig. 5. Navigation tracks of eight Chinese refrigeration factory ships obtained from AIS information during May and mid-September. The colors indicate the ship tracks of different cruises and the blue line indicates the Japanese and Russian EEZ border.

chub mackerel in this area. The freezing capacities of each fishing vessel were averaged from the values in the NPFC vessel list [25]. Results of the VIIRS DNB analyses (Table 1) were considered sufficiently reliable as a result of the comparison with AIS information, and were used to calculate the number of operating boats during the periods listed in Table 1. The ratio of fishing boat types (LPS: SDN, Table 2) was assumed to be proportional to the numbers of those ships appearing in the NPFC vessel list [25]. According to the industry information obtained from Chinese fishing companies, LPS caught 12.5 (MT day^{-1}) on average. The catch amount of SDN was assumed using the ratio of freezing capacity of these two fishing boats (12.5 × 98.9 / 27.8 MT day^{-1}). The operational factor was assumed to be 1.0 because the daily catch amount of LPS provided by Chinese fishing companies was reasonable enough as compared to daily catches by other fishing boats in Japan. This led to an estimation of approximately 153,000 MT as the total amount of catch based on the reliable light point data during the 84-day summer season.

It was difficult to estimate the amount transferred by fish carrier ships, because some carrier ships might be engaged in fish transfer from fishing boats to factory ships. Furthermore, according to AIS navigation records, some fish carrier ships went not only to their mother ports, but also to non-Chinese ports such as Meynypilgyno in Russia, directly from the fishing grounds. Additionally, AIS data was obtained from only a small number of ships due to their deliberate switching off of their AIS transponders and short stays in the fishing grounds, although 34 large carrier ships were listed in the NPFC list [25].

Two types of estimates were then conducted to bridge this data gap (Table 2). Estimate (A) was mainly based on the information from the NPFC list. The average fish hold capacities of the 34 large carrier ships was equivalent to 8845 MT of fish if freezing porosity is assumed to be 0.8 (Table 2). The AIS information suggested that some refrigeration factory ships showed a pattern of shuttling between China and the

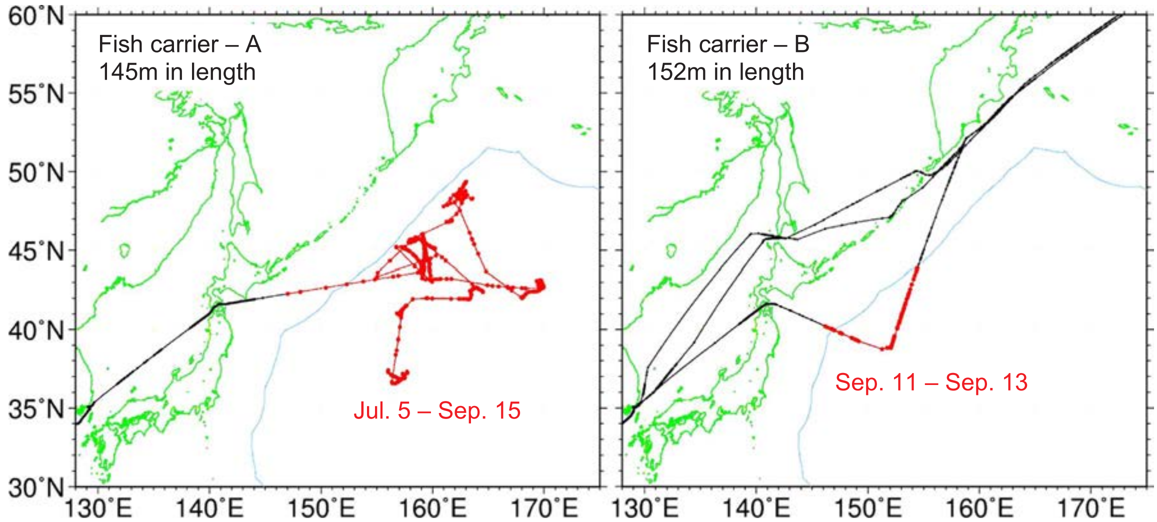

Fig. 6. Navigation tracks of two Chinese fish carrier ships obtained from AIS information during June and mid-September. The colors indicate the ship tracks of different cruises and the blue line indicates the Japanese and Russian EEZ border.

northwestern Pacific. These ships stayed in the fishing grounds from 10 to 20 days and cruised for 10 days (Fig. 5, RFS D-H). The operational factor was conservatively assumed to be 0.6, leading to an estimate of total transport of catches by the large carriers of approximately 549,200 MT during the 84 days of the summer season.

Another estimate (B) was based on information from interviews at fisheries companies. Three carrier ships were assigned to eight LPS boats and were shuttling between the fishing grounds and Chinese ports. These three ships operated in rotation, *i.e.,* one going to, one staying in and one coming back from, the fishing grounds. The average length of the stay in the fishing grounds was assumed to be 5 days, as this matched the rotation schedule. These fish carrier ships were not listed as fish carriers in the NPFC vessel list. The carrier ships were therefore assumed to transfer the fish caught by the number of fishing boats operating in Area A (maximum number: 139 light points during July 31st to August 1st, Table 1). Again, a conservative operational factor (0.6) was assumed, which resulted in an estimate of the total amount of transport by the carrier ships of approximately 210,200 MT during the 84 days of the 2016 summer season.

Average fish hold capacity of refrigeration factory ships was assumed to be equal to the capacity reported in the NPFC vessel lists [25], which was an equivalent to 2211 MT of fish, assuming a freezing porosity of 0.8 (Table 2). The navigation tracks of eight refrigeration factory ships suggested the number of ships staying at the fishing ground (Fig. 5). The total number of ship-days staying in the fishing ground was estimated to be 439 (ships × days) from the data of Fig. 5. This estimated number of factory ships could process approximately 52,700 MT during the 84 days of the summer season based on the daily freezing capacity from interviews at Chinese fishing company. The estimated carrying amount, when they left the fishing grounds, was approximately 19,300 MT.

This additional 19,300 MT, which was transported by the refrigeration factory ships themselves, was added to the estimated amount calculated both from estimate (A) and (B) (Table 2). The estimated total transported amount was thus 568.500 MT for estimate (A) and 229,500 MT for estimate (B) during the 84 days of the summer season (Table 2). The actual amount of fish transported by these fish carriers is likely to fall between the two estimates, 229,500–568,500 MT, because the estimate (B) was conservative based on the VIIRS DNB data in this area with the information obtained from a Chinese fishing company. Further details on the summarized estimates from the NPFC vessel lists and the analyses of the interviews at Chinese fisheries companies can be found in Supplementary material.

4. Discussion

Integration analyses of VIIRS DNB data and AIS information provided several benefits for the analysis of fishing activities, since the analyses also allowed us to trace the movements of fishing grounds and target fish species as well as to identify the fishing grounds of a given flag nation's fishing boats. It was observed that many fishing boats usually grouped together when searching for schools of fish. Three groups of fishing boats were identified in July in the target research area. According to the sea surface temperature and their main fishing area, each group appeared to target a different species. The target species of Group A, B, and C appeared to be chub mackerel (SST 15–20 °C [20]), pacific saury (SST 11–15 °C [31]) and neon flying squid, *Ommastrephes bartramii*, (SST 11–15 °C [4,35]), respectively. Group C then merged with Group A to catch chub mackerel as the target species after August, while Group B continued to catch pacific saury. From the above findings, light point distributions described in this study with the aid of AIS information were consistent with the biological distributions of fished species and were considered to be reliable enough to estimate the fishing activities of Chinese fishing boats using fish aggregation lights in the northwestern Pacific.

The integration analyses revealed another important point: that most of the fishing boats stayed for long periods in the area, resulting in a large quantity of fish being transferred to fish carrier ships directly or *via* refrigeration factory ships. This type of Chinese fisheries operation has been reported to have become popular in Chinese distant-water fisheries since the onset of the 21st Century [17,26]. Sightings from Japanese research vessels confirmed, in 2015, the presence of large cargo ships operating under the Panamanian flag of convenience in addition to Chinese and Russian cargo ships (personal com., J, Abo). The navigation tracks of eight refrigeration factory ships, monitored from AIS data, presented useful information for estimating their amount of catch. Following the results shown in Fig. 5, three refrigeration factory ships played the role of mother factory ships in the fishing grounds. Fish products were transferred from them to other fish carrier ships. Shuttle-like navigation tracks observed for the other five refrigeration factory ships provided information on their cruise schedule, backed up by interviews at Chinese companies. The navigation tracks of fish carriers also provided information on their cruise schedules, although the data were limited because of the occasional absence of AIS signals.

Table 2
Estimated catch amounts of chub mackerel from June 14th to September 5th by Chinese fisheries in the northwestern Pacific based on different approaches. Details of data with an asterisk can be found in Supplementary material.

Operation of fishing boats		
Number of operation (day^{-1})		Light points data in Table 1
Ratio of fishing gear (SDN: LPS)	84:53	Estimated from NPFC vessel lists*
Catch amount (LPS: MT day^{-1})	12.5	From interviews at Chinese fishing company*
(SDN: MT day^{-1})	44.5	Extrapolated by the ratio of freezing capacity
Estimated catch (MT) (F:1.0)	**153,084**	Operational factor (F): 1.0–0.6
(F:0.8)	122,467	
(F:0.6)	91,850	
Operation of fish carrier ships (A)		
Number of boats	34	From NPFC vessel lists*
Days to fill (DF: days)	10–20	Estimated from Fig. 5
Cruise duration (days)	10	Estimated from Fig. 5
Freezing porosity	0.8	From data on Japanese purse seiners
Carrying capacity (MT)	8845	Average fish hold capacity in NPFC vessel lists*
Estimated amount (MT) (DF:10, F:0.6)	823,742	Operational factor (F): 1.0 – 0.6
(DF:15, F:0.6)	658,994	
(DF:20, F:0.6)	**549,161**	
Operation of fish carrier ships (B)		
Estimated number of ships		(Max light point day^{-1})/8 × 3 from Table 1, From interviews at Chinese fishing company*
Days to fill	5	From interviews at Chinese fishing company*
Cruise duration (days)	10	From interviews at Chinese fishing company*
Carrying capacity (MT)	1200	From interviews at Chinese fishing company*
Estimated amount (MT) (F:1.0)	350,280	Operational factor (F): 1.0–0.6
(F:0.8)	280,224	
(F:0.6)	**210,168**	
Operation of refrigeration factory ships		
Number of ships	8	Data from Fig. 5
Ship-days of staying (ships × day)	439	Data from Fig. 5
Freezing capacity (MT day^{-1})	120	From interviews at Chinese fishing company*
Freezing porosity	0.8	from the data of Japanese purse seiner
Fish hold capacity (MT)	2211	Average freezing capacity in NPFC vessel lists*
Estimated total freezing (MT)	52,680	
total carrying (MT)	**19,347**	

Total estimated catch = **153,084** (MT).
Estimated positive transport (A).
= **549,161** (MT, carrying-A) + **19,347** (MT, carried by factory ships) = **568,508** (MT).
Estimated positive transport (B).
= **210,168** (MT, carrying-B) +**19,347** (MT, carried by factory ships) = **229,515** (MT).

Information found in this study enabled the estimation of the total catch amount from a certain fishing ground with the aid of descriptive information on fishing operation, *e.g.*, fishing duration, daily catch and number of tows at a night, and operation of fish carrier ships. The catch amount, estimated at 153,000 MT during the 84 days of the summer season, was reliable due to the realistic light point data owing to the Chinese fishing boats being supported by the AIS information. The transferred amount from the fishing boats to fish carrier ships was difficult to estimate because the amount of loading cannot be detected from outside. The estimated transported amount in this study, between 229,500 MT (Estimate B) to 568,500 MT (Estimate A) during the 84 days of the summer season, was conservative under these difficult circumstances. These estimates for transport showed a wide range in value and were much greater than the catch estimates based on the light point data (153,000 MT). However, it does not seem particularly unrealistic, since fish carrier ships transfer a range of species caught in the northwestern Pacific, including not only chub mackerel but also pacific saury and neon flying squid. These estimates were much more realistic than the previous analyses, even in a restricted area, so accumulation of these estimates around the world has the potential to improve previous estimates of amounts caught by IUU fisheries [26].

Seasonal changes of light points in this area suggest that fishing activities continued from June to November in the last three years and have increased in 2016 (Fig. 3). Information obtained from interviews suggests that the fishing boats stayed in the fishing grounds from early July to early November. This means that the total estimation of catch in this area may well be more than double the estimated amount for 84 days in summer, and suggests that more than 306,000 MT of chub mackerel were caught in 2016 on the high seas. This is a very significant amount in comparison with the Japanese total allowable catch (TAC) of mackerel, which was set based on the allowable biological catches (ABC; 383,000 MT [14]) for the northwestern Pacific in the 2016 fishing season, although the estimates may include the amounts taken by IUU fishing boats. Japan has continued stock assessment of chub mackerel for more than the last two decades. The most recent results show that the stock level remained at a low level from 153,000 MT (2001) to 1353,000 MT (2015) and that its spawning stock biomass (SSB) was mostly in this period lower than 450,000 MT, which in 2014 qualified this stock as a proposed biological target for recovery (B_{limit}) [36]. The B_{limit} was finally achieved after over ten years of conservation efforts by the JFA and Japanese fishermen [36]. The Japanese scientists recommended ABCs that would maintain SSB above B_{limit}, so as to stabilize recruitment from year to year. Upon this recommendation, the TAC for chub mackerel in 2016 was set based on the information of ABC in the north Pacific region [14].

Japanese fishery patrol vessels observed significant numbers of fishing boats carrying false ship names and false MMSI records and AIS information in this area [15]. Previous studies have identified significant concerns with Chinese domestic catch estimates, suggesting that China over-reports its domestic catch and declares improbably low catches in its distant water fishing fisheries [26]. The recent rapid increase in Chinese fishing operations in the northwestern Pacific suggests that the estimates in this study are not unreasonably high, even from a conservative viewpoint. The amount is more than double the 2016 catch reported from China to NPFC (142,994 MT [16]). This level of Pacific high seas fishing is likely to have a very significant impact on the future of fish abundances, in particular that of chub mackerel. The spawning grounds of the chub mackerel remain in the Japanese EEZ, but the nursery grounds extend into the high seas. The rapid expansion of Chinese high seas fishing is, therefore, likely to have significant adverse effects on the recovery of this stock. To assess the actual impact of the Chinese high seas catch on the chub mackerel stock, it is more important than ever to estimate a catch amount independently from the reported catch data. Drastic policy reforms have been reported for Chinese fisheries in recent years with a focus on the protection of marine ecosystems to encourage the sustainable use of marine resources [3]. Legislation to reduce fishing pressure has been implemented, especially for coastal areas; however, the rapid expansion of Chinese distant-water fisheries is having an increasing impact on marine ecosystems in high seas areas.

5. Conclusion

The fundamental nature of IUU fishing means that there is very little data available on the level of IUU fishing effort or catch. Its activities are unreported and thus unknown. Without data on actual IUU fishing activities or their supporting systems, it is virtually impossible to develop proper measures to counteract it. The method used in this study suggests the promising potential of this new tool for monitoring unregulated fishing activities. The greater the volume of data and the more refined its use, the more accurate will be the monitoring of such activities all year around. The analyses conducted in this report could not fully cover all fishing boats, including potential IUU boats, operating in this area. Boats using false names or false MMSI codes for AIS have been sighted by Japanese patrol vessels over the last three years [14]. Chinese fishing companies have themselves mentioned the presence of fishing boats called “fishing boats without three types of information (no name, no registration and no fishing license),” during interviews. The current situation in the northwestern Pacific fishery might well be worse than this study suggests. Additionally, the NPFC, a newly established RFMO, seems to be facing tremendous difficulties in taking quick action to ensure the sustainability of the relevant resources, including chub mackerel [24]. Unless urgent action is taken, the future of these resources is doomed.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2017.11.009.

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