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Hiroto Murase, Tsutomu Tamura, Seiji Otani, Shigetoshi Nishiwaki

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Satellite tracking of Bryde's whales *Balaenoptera edeni* in the offshore western North Pacific in summer 2006 and 2008

Hiroto Murase[1,2] · Tsutomu Tamura[1] · Seiji Otani[1] · Shigetoshi Nishiwaki[1]

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Abstract Movements of two individual Bryde's whales (*Balaenoptera edeni*) were recorded using satellite-monitored radio tags in the offshore western North Pacific where no such data had been recorded. One individual was recorded for 13 days 4 h 57 min from 13 to 26 July 2006. The total traveled distance of the individual was 917.3 km with a mean speed of 2.9 km/h. The other individual was recorded for 20 days 5 h 5 min from 24 July to 13 August 2008. The total traveled distance of the individual was 2649.7 km with a mean speed of 5.5 km/h. It has been documented that the subarctic-subtropical transition area (around 40°N) is one of the feeding areas of Bryde's whales in summer. However, the results revealed that some individual Bryde's whales moved from the subarctic-subtropical transition area to the subtropical area even in summer. The observation indicated Bryde's whales did not stay in a feeding area persistently throughout summer. This study provides the first information regarding the continuous movement of Bryde's whales in the offshore western North Pacific in summer which enhances understanding of their life history.

Keywords Distribution · Feeding ground · Habitat · Marine mammal · Migration · Movement · Telemetry

✉ Hiroto Murase
muraseh@affrc.go.jp

1 The Institute of Cetacean Research, 4-5 Toyomi-cho, Chuo-ku, Tokyo 104-0055, Japan

2 Present Address: National Research Institute of Far Seas Fisheries, Fisheries Research Agency, 2-12-4 Fukuura, Kanazawa, Yokohama, Kanagawa 236-8648, Japan

Introduction

Information regarding the movement of baleen whales is important to understanding their crucial distribution areas and for their management. Long-term (weeks to months) study is required to reveal distribution areas of baleen whales as they migrate long distances between breeding and feeding grounds. Marking tags, known as "Discovery tags", were used to study whale movement in earlier years [1]. However, the practice was ended as a moratorium of commercial whaling was imposed in the 1980s because the tags shot into the bodies of whales had to be recovered by catching these individuals. The tags could only provide two locations (locations of deployment and recovery) and paths between two locations were unknown. Photographic matching of natural external markings has also been used to study movement of whales with successful results [2, 3]. However, as in the case of the Discovery tags, photographic matching could only provide locations where photographs were taken and movement between these locations was unknown. Moreover, recapturing of tagged and photographed individuals is difficult if target species are abundant and/or distributed in areas remote from land. Attempts to monitor continuous movement of baleen whales using satellite-monitored radio tags was started in the 1980s [4] and they have been deployed to most baleen whale species, such as right *Eubalaena* spp. [5–8], bowhead *Balaena mysticetus* [9–14], blue *Balaenoptera musculus* [15–20], fin *B. physalus* [20–25], sei *B. borealis* [26], common minke *B. acutorostrata* [27, 28], humpback *Megaptera novaeangliae* [11, 29–35] and gray *Eschrichtius robustus* [36–39] whales. However, no result for Bryde's whales *Balaenoptera edeni* has been reported in scientific literature, except for a doctoral thesis [40], probably because their oceanic distribution inhibits access from scientists.

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Though the occurrence of three species of the Bryde's whale complex, namely, Bryde's whale *B. brydei*, Eden's whale *B. edeni* and Omura's whale *B. omurai* has been indicated [41], some scientists consider the former two forms to be subspecies, *B. e. brydei* and *B. e. edeni*, rather than species, as indicated by the Committee on Taxonomy of the Society for Marine Mammalogy (Committee on Taxonomy, "List of Marine Mammal Species and Subspecies", Society for Marine Mammalogy: http://www.marinemammalscience.org "accessed on 19 February 2015") and Kato and Perrin [42]. The scientific committee of the International Whaling Commission (IWC/SC) treats these taxa (apart from Omura's whale) as *B. edeni* with Bryde's whale as the common name, but recognizes that more than one species exists [43]. It was reported that the species distributed in our study area (i.e. offshore western North Pacific) was identified as *B. brydei* while those in coastal areas of southwestern Japan were identified as *B. edeni* based on a genetic study [44] in the sense of Wada et al. [41]. However, other authors treated them as two different stocks of *B. edeni* in the sense of the IWC, namely the western North Pacific and East China Sea stocks, respectively [40, 45]. Furthermore, differences between Bryde's whales in various regions of the world have not been investigated fully on a global basis [42], although relationships between geographic sampling locations and the phylogenetic position for Bryde's whale control-region haplotypes have been investigated on a global basis using published data [46]. We follow the nomenclature defined by the IWC because taxonomy is not the main subject of this paper.

In the offshore western North Pacific, Bryde's whales are distributed in the subarctic-subtropical transition area in summer [47, 48] as one of the feeding grounds [49–51]. Past studies of Bryde's whale movement in the offshore western North Pacific using the Discovery tags suggested they stayed in the low latitudes (0°–10°N) in winter (January to March) and then migrated to middle latitudes (20–40°N) in spring and summer (April to August), although some individuals stayed in the middle latitudes from winter to summer [40]. The estimated abundance of the western North Pacific stock in the period of 1998–2002 was 20,501 individuals [52]. The estimated rate of annual increase from 1988 to 2002 was 4.1 % [53]. Based on photographic matching of individuals, local movement of Bryde's whales was identified in coastal areas of southwestern Japan [40], the Gulf of California [54] and south eastern Brazil [55]. These individuals could be considered as local residents. It is expected that photographic matching in offshore regions is technically and logistically difficult because the abundance and target area are large in comparison with coastal areas. These could be some of the reasons why such an attempt has not been made. There is no information on the continuous movement of Bryde's whales in the offshore western North Pacific during summer. Understanding of movement Bryde's whales in the offshore western North Pacific is important for management of this species distributed in this area. It should be noted that Kishiro [40] deployed satellite tags to individuals belonging to the East China Sea stock of this species.

In this paper, movement of Bryde's whales in the offshore western North Pacific in summer 2006 and 2008 was studied by using satellite-monitored radio tags. Satellite-derived sea surface temperature (SST), sea surface chlorophyll-a concentration (CHL) and sea surface height anomaly (SSHA) data were used to understand oceanographic conditions encountered by the tagged individuals. It is expected that distribution of Bryde's whales is related to distribution of their prey, but such data are not available for this study. These environmental data are commonly used in habitat modelling studies of cetaceans as proxies for their prey abundance or availability [56]. This is the first report of satellite tracking of Bryde's whales in this region.

Materials and methods

Two satellite tags were attached to Bryde's whales in the offshore western North Pacific in 2006 and 2008 (one tag for each year) as a part of the second phase of the "Japanese Whale Research Program under Special Permit in the western North Pacific" (JARPNII; Table 1; Figs. 1, 2). The program was conducted under a permit issued by the government of Japan. The individual in 2006 was accompanied by a calf with an estimated body length of 8.7 m, as estimated visually from the research vessel. The transmitters used in the study were the "TCU-150 Argos Platform Transmitter Terminal System" (PTT, Telonics Inc., Arizona, USA) equipped with salt water switches. Locations of the Argos satellite transmitters were provided through the "Collecte Localisation Satellites" (CLSs,

Table 1 Summary of satellite tracking of two individual Bryde's whales in 2006 and 2008

Year	Attachment			End			Body length (m)	Duration	Traveled distance (km)	Mean speed (km/h)
	Date	Latitude	Longitude	Date	Latitude	Longitude				
2006	13 Jul.	37°36.5′N	155°10.4′E	26 Jul.	31°16.3′N	153°34.4′E	12.5	13 days 4 h 57 min	917.3	2.9
2008	24 Jul.	38°00.1′N	147°51.5′E	13 Aug.	24°02.1′N	164°46.4′E	12.6	20 days 5 h 5 min	2649.7	5.5

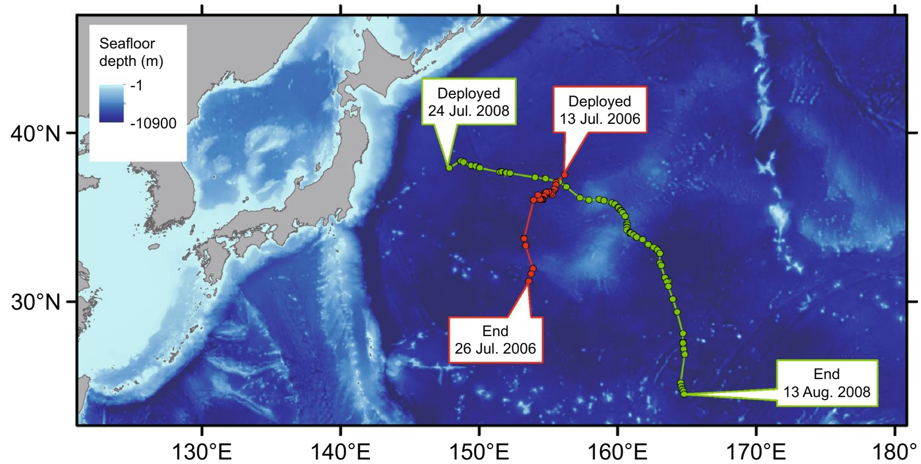

Fig. 1 Movements of two individual Bryde's whales in 2006 and 2008 monitored by satellite tags. *Circles* represent positions of signals. Location classes 1–3 are used in the figure. (A color version of this figure is available in the portable document format (PDF) version of this article)

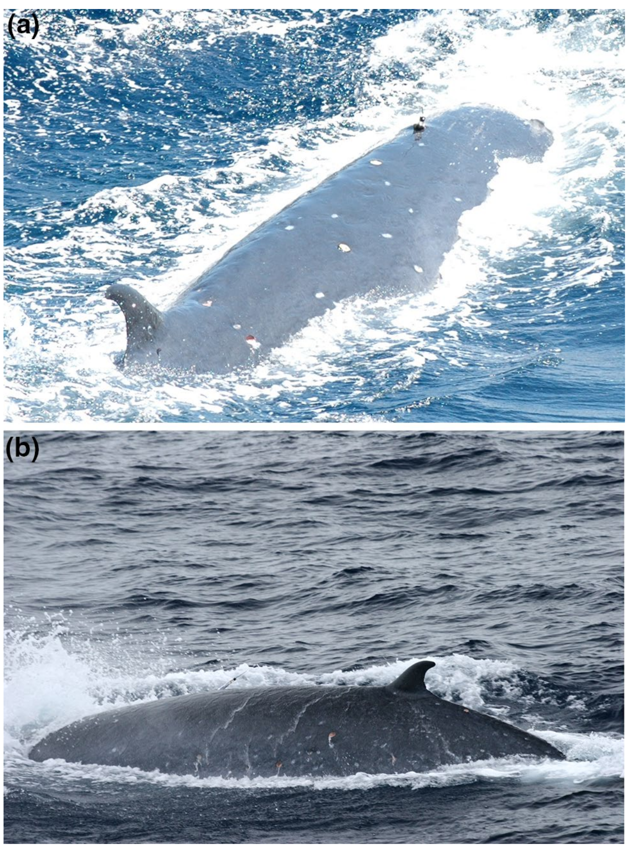

Fig. 2 Bryde's whales tagged in 2006 (**a**) and 2008 [**b**; A color version of this figure is available in the portable document format (PDF) version of this article]

Ramonville-Saint-Agne, France). The switches allowed transmissions when the tags were out of the waters. The transmitters were encapsulated in polycarbonate cylinders with stainless harpoon heads (Fig. 3). The harpoon heads were tethered to the stainless shaft with an expectation that the harpoon heads were fixed in the body tightly. The antennas of the transmitters were covered by other polycarbonate cylinders when the tags were deployed from the gun. The covers could be detached once it hit whales. The nylon strings were attached to the tags so that they could be retrieved when the shots were missed. The tags were deployed by an air gun, called as the ICR (Institute of Cetacean Research, Tokyo, Japan) gun, which was a modification of the marine safety pneumatic line thrower [57]. The tags were shot from the bow deck of the survey vessels. *Yushin Maru* No. 2 (747GT) and *Yushin Maru* (720GT) were used in 2006 and 2008, respectively. The lengths of the vessels are about 70 m and the height of the bow decks from sea surface is about 8 m. The effective shooting range of the gun is approximately 25 m. The shooting distance between the gun and the individuals in 2006 and 2008 were approximately 10 and 20 m, respectively.

The CLSs provide theoretical accuracy of locations (location class: LC), as shown in Table 2. The CLSs do not provide the accuracy for LCs-0, A and B. Several at-sea measurements of the accuracy were conducted as reviewed by Costa et al. [58] and their estimated accuracy is also shown in Table 2. In this paper, only LCs-1, 2 and 3 were considered to calculate distance and time of travel between consecutive points.

SST data (4 × 4 km grid) obtained by a moderate resolution imaging spectroradiometer aboard the Terra satellite (Terra MODIS) were used. CHL data (4 × 4 km grid) obtained by a sea-viewing wide field-of-view sensor (SeaWiFS) aboard GeoEye's OrbView-2 were used. Monthly means of July 2006 and rolling 32-day composites (19 July–19 August 2008) in level 3 SST and CHL products were downloaded from "Ocean Color Web" (http://oceancolor.gsfc.nasa.gov/, NASA Goddard Space Flight Center, "last accessed on 22 December 2013") were used. Missing

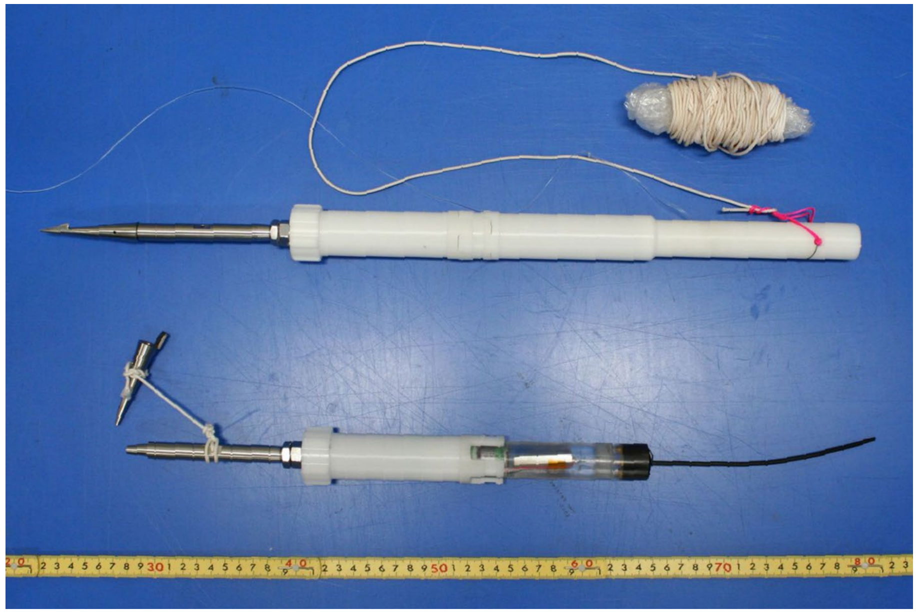

Fig. 3 The tag attached to Bryde's whales in 2006 and 2008. The satellite transmitter was encapsulated in a polycarbonate cylinder with a stainless harpoon head (*bottom*). The antenna of the transmitter was covered by another polycarbonate cylinder when the tag was deployed from the gun (*top*). The cover could be detached once it hit whales. The harpoon heads were tethered to the stainless shaft with an expectation that the harpoon heads were fixed in the body tightly. [A color version of this figure is available in the portable document format (PDF) version of this article]

Table 2 Accuracy of satellite tag locations (latitude/longitude in km) provided by the CLSs and measured by Costa et al. [58]

Location class (LC)	Accuracy (km)	
	CLS	Costa et al. [58]
Statistics	68th percentile	68th percentile
LC-3	0.15/0.15	0.225/0.340
LC-2	0.35/0.35	0.468/0.729
LC-1	1.00/1.00	0.574/0.879
LC-0	–	1.795/2.855
LC-A	–	2.788/4.373
LC-B	–	4.642/8.253
LC-Z	No location	No location

Table 3 Number of received signals from two individual Bryde's whales in 2006 and 2008 by location class

Location class (LC)	Number of signals			
	2006		2008	
LC-3	1	1 %	4	1 %
LC-2	8	5 %	27	9 %
LC-1	15	9 %	33	10 %
Subtotal	24	15 %	64	20 %
LC-0	14	9 %	27	9 %
LC-A	48	30 %	63	20 %
LC-B	67	42 %	74	23 %
LC-Z	5	3 %	88	28 %
Subtotal	134	85 %	252	80 %
Total	158	100 %	316	100 %

data in these data were estimated by ordinary kriging with the aid of the geographic information system (GIS), ArcGIS 10.1 (ESRI, California, USA). Maps of sea level anomalies and geostrophic velocity anomalies (MSLAs) were also used in this study. Daily data of sea surface height anomalies (SSHAs) recorded on the middle day of the data recording periods (19 July 2006 and 6 August 2008) were used in the paper because only daily data were available. The altimeter products were produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes (http://www.aviso.oceanobs.com/duacs/ "accessed on 29 January 2010"). Cross-sections of SSTs, CHLs and SSHAs encountered by the tagged individuals were also prepared by using ArcGIS. The "ETOPO1 Global Relief Model for bottom topography" [59] was used as seafloor depth data for illustrative purpose. "A Global Self-consistent, Hierarchical, High-resolution Geography Database" [60] was used in figures to depict coastlines.

Results

Movement of one Bryde's whale (estimated body length: 12.5 m) was recorded for 13 days 4 h 57 min from 13 to 26 July 2006 (Table 1). A total of 158 signals were received (Table 3). Among them, 24 signals were LCs 1–3 (15 % of total signals). Daily means (minimum and maximum) of signal numbers (all classes) was 10.33 (4–17). The number of signals (excluding LC-Z) in daytime (sunrise to sunset) and nighttime (sunset to sunrise) was 90 and 59, respectively. LC-Z was excluded because location data were necessary to calculate local time. Speed of movement in Table 1 was calculated using total traveled distance divided by total traveled time. The total traveled distance of the individual was 917.3 km with a mean speed of 2.9 km/h. Mean (minimum and maximum)

Table 4 Means (minimum and maximum) of distance and duration between two consecutive locations calculated by received signals from two individual Bryde's whales in 2006 and 2008

Year	Distance (km)		Duration	
	2006	2008	2006	2008
Mean	20	41	6 h 59 min	7 h 34 min
Standard deviation	58	42	19 h 0 min	7 h 41 min
Maximum	261	210	74 h 8 min	33 h 34 min
Minimum	0.4	0.6	25 min	1 min

Location classes 1–3 are used for the calculations

distance and duration between two consecutive locations were 20 km (0–261) and 6 h 59 min (25 min–74 h 8 min), respectively (Table 4). Minimum and maximum speeds between two consecutive locations were 0.1 and 6.5 km/h, respectively. It should be noted that the distance between the positions of the satellite tags might not be actual movement path of the whale as two consecutive points had long time durations. Therefore, the speed of movements calculated by using distance between two consecutive positions can be considered as not actual but minimum speed. Principally, the individual moved southward (Fig. 4). SSTs encounter by the individual increased as it moved south. SSHAs encounter by the individual showed no consistent changes. CHLs encounter by the individual decreased as it moved south. Summary statistics of SSTs, SSHAs and CHLs encountered by the tagged individual are shown in Table 5. Mean (minimum and maximum) SSTs, SSHAs and CHLs were 22.6 °C (19.0–24.9), 1.2 cm (−29.2 to 30.2) and 0.13 mg/m^3 (0.07–0.18), respectively.

Movement of the other Bryde's whale (estimated body length: 12.6 m) was recorded for 20 days 5 h 5 min from 24 July to 13 August 2008. A total of 316 signals were received. Among them, 64 signals were LCs 1–3 (20 % of total signals). The daily mean (minimum and maximum) of signal numbers (all classes) was 14.36 (1–20). The number of signals (excluding LC-Z) in the daytime and nighttime were 114 and 110, respectively. The total traveled distance of the individual was 2649.7 km with a mean speed of 5.5 km/h. Mean (minimum and maximum) distance and duration between two consecutive locations were 41 km (1–210) and 7 h 34 min (1 min–33 h 34 min), respectively. Minimum and maximum speeds between two consecutive locations were 1.4 and 26.4 km/h, respectively. Principally, the individual moved eastward then southward (Fig. 5). SSTs encounter by the individual increased as it moved south. SSHAs encounter by the individual showed no consistent change. CHLs encounter by the individual decreased as it moved south. Means (minimum and maximum) of SST, SSHAs and CHLs were 25.7 °C (23.3–28.7), 6.5 cm (−30.9 to 35.9) and 0.09 mg/m^3 (0.03–0.15), respectively.

The mean speed for the two individuals calculated using total traveled distance divided by total traveled time was 4.4 km/h.

Discussion

The results of this study showed two Bryde's whales monitored by satellite tags moved southward from the subarctic-subtropical transition area (around 40°N) to the subtropical area of the offshore western North Pacific in summer (July and August). The approximate location of the subarctic front is around 40°N in this area [61]. The subarctic-subtropical transition area of the western North Pacific can be considered as one of the feeding areas of Bryde's whales in summer. However, this study revealed that some individual Bryde's whales moved from the subarctic-subtropical transition area to the subtropical area, even in summer. The observations indicated that Bryde's whales did not stay in a feeding area persistently throughout summer. Historical commercial catch and sighting data indicated that Bryde's whales were also distributed to the equator in the offshore western North Pacific in summer [62]. The results of a species distribution model (SDM) using a generalized linear model (GLM) indicated that the subarctic-subtropical transition area was the northern edge of Bryde's whale distribution in the western North Pacific in the summer, and the estimated probability of occurrence was high in the south of the area [48]. The results of the Discovery tags indicated that Bryde's whales did not migrate north of 40°N [40]. Combining the past knowledge and the results of this study, the subarctic front can be considered as the northern limit of the distribution area of Bryde's whales in the western North Pacific. The results of this study indicate that the northbound migrants of Bryde's whales could change their swimming direction southward after they encounter the front. In the subarctic-subtropical transition area, Bryde's whales mainly fed on krill and Japanese anchovy *Engraulis japonicus* [49–51]. In the south of the area (area approximately bounded by 20°N, 35°N, 160°E and 170°W), they mainly fed on krill, *Euphausia similis* and *Nematoscelis difficilis*, and oceanic lightfish *Vinciguerria nimbaria*, but they also fed on a variety of fish species such as Indian scad *Decapterus lajang*, synonym for *Decapterus russelli*, Lovely hatchetfish *Argyropelecus aculeatus*, Prickly lanternfish *Myctophum asperum*, Bertelsen's lanternfish *Diaphus bertelseni* and *Polypnus* (note: the spelling is shown in the reference but it could be *Polyipnus*) *matsubarai* [63]. The feeding area of Bryde's whales might not be restricted to the subarctic-subtropical transition area in summer as they feed on a variety of prey species (krill, small pelagic

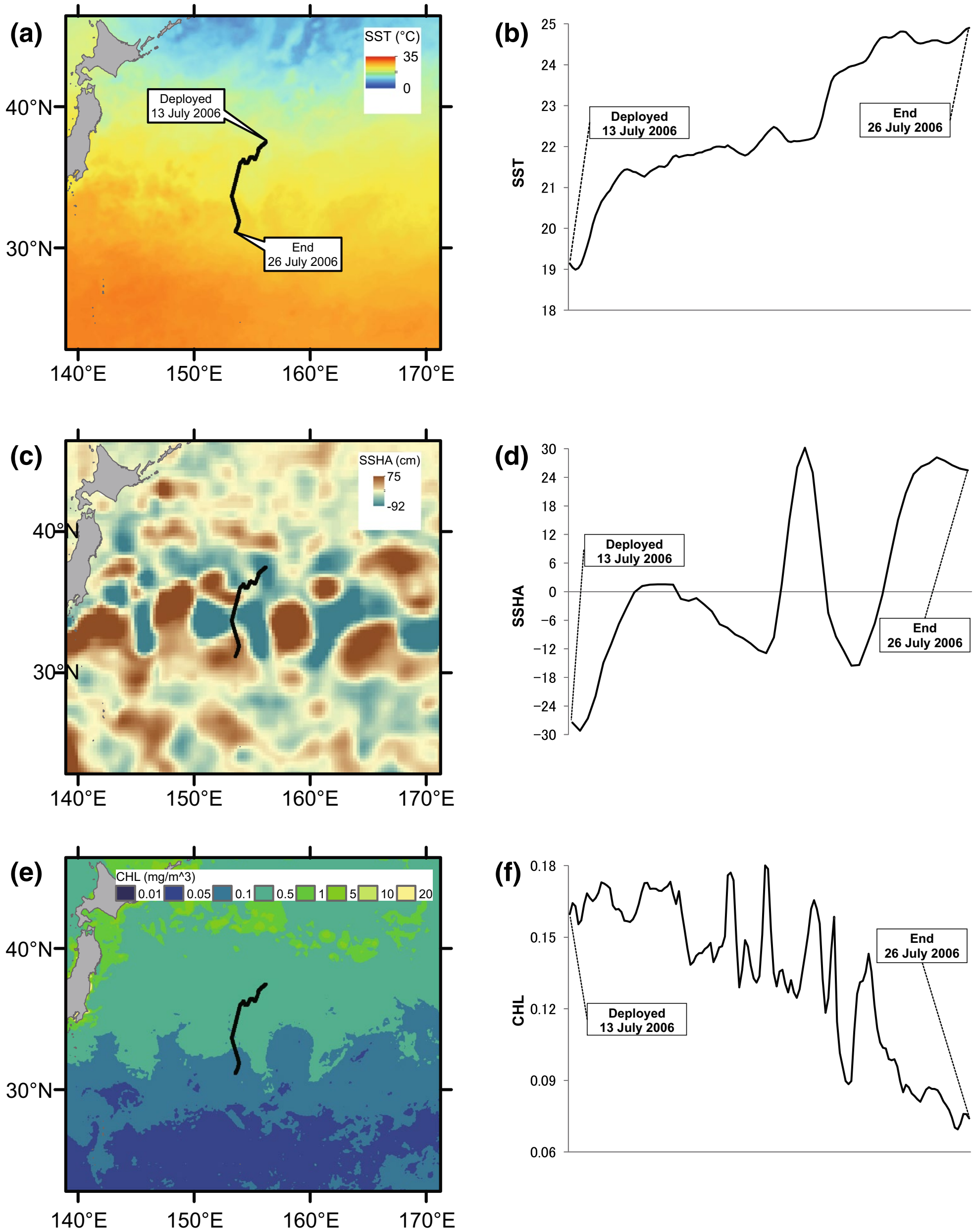

Fig. 4 Sea surface temperature (SST; **a**, **b**), sea surface height anomaly (SSHA; **c**, **d**) and sea surface chlorophyll-a concentration (CHL; **e**, **f**) encountered by a Bryde's whale in 2006. *Black line* in the map represents the track of movement of the individual [A color version of this figure is available in the Portable Document Format (PDF) version of this article]

Table 5 Means (minimum and maximum) of sea surface temperature (SST), sea surface height anomalies (SSHAs) and sea surface chlorophyll-a concentrations (CHLs) encountered by two individuals Bryde's whales in 2006 and 2008

Year	SST (°C)		SSHA (cm)		CHL (mg/m^3)	
	2006	2008	2006	2008	2006	2008
Mean	22.6	25.7	1.2	6.5	0.134	0.087
Standard deviation	1.6	1.4	16.4	15.8	0.033	0.039
Maximum	24.9	28.7	30.2	35.9	0.180	0.153
Minimum	19.0	23.3	−29.2	−30.9	0.069	0.034

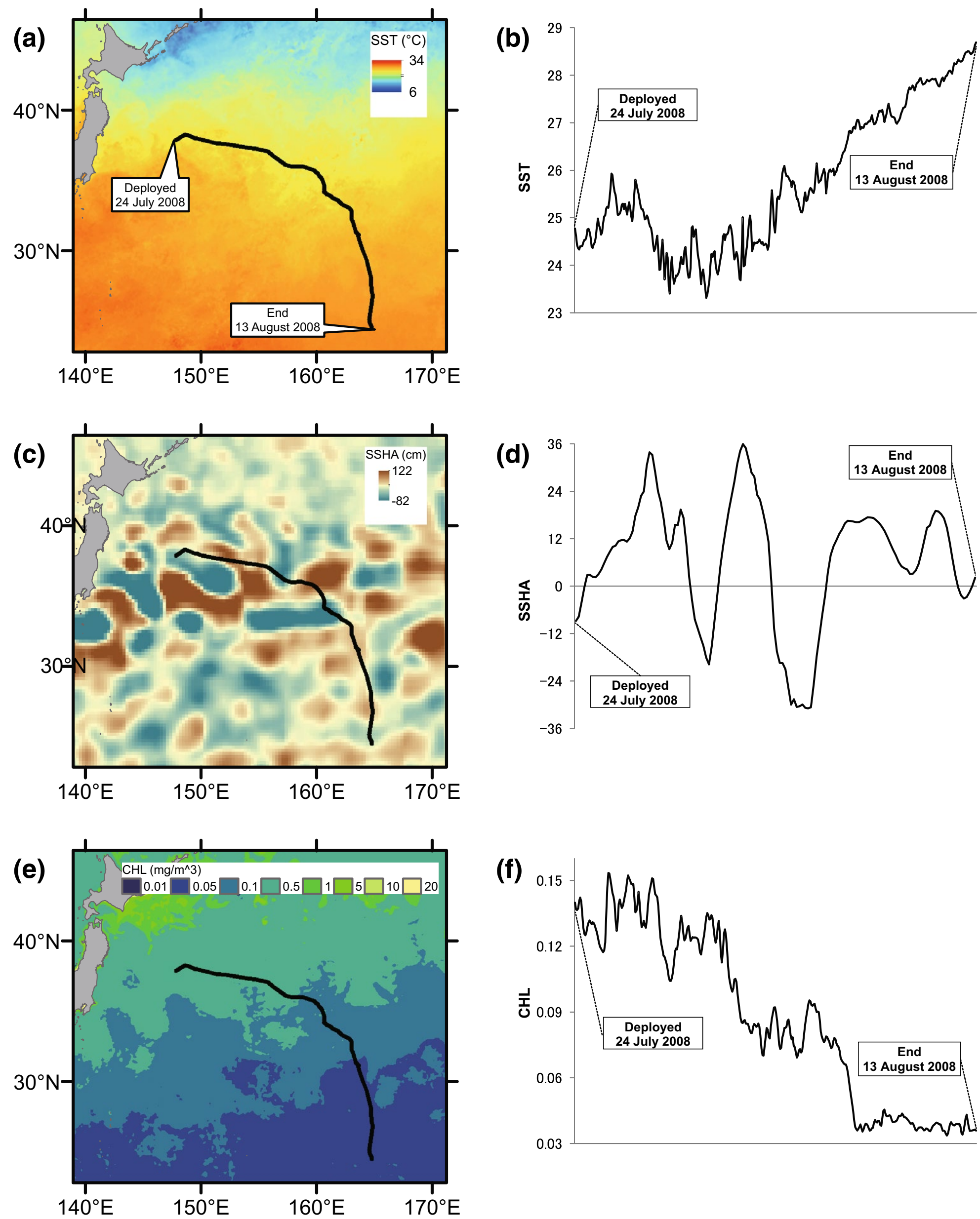

Fig. 5 Sea surface temperature (SST; **a**, **b**), sea surface height anomaly (SSHA; **c**, **d**) and sea surface chlorophyll-a concentration (CHL; **e**, **f**) encountered by a Bryde's whale in 2008. The *black line* in the map represents the track of movement of the individual. [A color version of this figure is available in the portable document format (PDF) version of this article]

and mesopelagic fishes) in various parts of the western North Pacific. The southward movement observed in this study could be (1) seasonal migration, (2) movement within feeding areas and/or (3) other reasons (e.g. associated with social behavior). However, it is difficult to make any conclusion based only on data from two individuals with a relatively short tracking duration.

Reported swimming speeds of baleen whales estimated by using satellite tag data are summarized in Table 6. Because calculation methods of the speeds were varied from paper to paper, and the speeds calculated using satellite tag data might not be actual swimming speeds, comparison of swimming speeds among baleen whales based on this table is only for reference. Nevertheless, swimming speeds of Bryde's whales calculated in this study are comparable to other baleen whales.

It was expected that Bryde's whales stayed around the subarctic-subtropical transition area of the western North Pacific in summer as the area was considered as their important feeding ground. However, this study revealed that the

Table 6 Comparison of swimming speed (km/h) of baleen whales from different studies calculated by using data obtained by satellite tags

Species	Mean	Standard deviation	Range		References
			Maximum	Minimum	
Right whale	3.3	–	–	–	[5]
	–	–	6.5	1.1	[6]
	2.7	1.3	4.6	0.8	[7]
Bowhead whale	–	–	4.5	0.9	[10]
	3.8	1.4	5.8	1.1	[13]
Blue whale	–	–	3.7	1.1	[15]
	2.5	2.7	–	–	[17]
	4.5	1.4	7.2	2.4	[19]
	–	–	6.5	4.2	[20]
Fin whale			7.7	2.5	[20]
	–	–	0.8	0.5	[23]
	1.5	–	–	–	[25]
Sei whale	3.7	4.0	–	–	[26]
Bryde's whale	4.4	–	5.5	2.9	This study
Common minke whale	–	–	3.3	2.7	[27]
	–	–	7.3	0.3	[28]
Humpback whale	1.3	0.7	3.1	0.7	[29]
	5.4	–	6.5	4.3	[31]
	–	–	5.9	1.0	[33]
	3.8	0.6	6.3	2.5	[34]
	–	–	3.8	0.8	[35]
Gray whale	–	–	5.9	1.1	[36]
	1.0	–	2.2	0.4	[37]
	5.6	–	–	–	[38]

Mean swimming speed and the range (maximum and minimum) is summarized in the table. Note that because calculation methods of the speeds were varied from paper to paper and the speeds calculated by using satellite tag data might not be actual swimming speeds, comparison of swimming speeds among baleen whales based on this table is only for reference

tagged individuals showed southward movement even in summer. The results implicate the limitations of interpreting SDM results (e.g. Sasaki et al. [48]) as pointed out by Palacios et al. [64]. SDMs may only estimate spatial distribution of individuals given certain environmental conditions at a certain time period. In that sense, SDMs are considered snapshot models that could overlook the dynamics of an individual whale's movement, as indicated by satellite tracking studies. However, it should be note that data obtained by satellite tags only provides the locations where tagged individuals are present. In addition, the number of satellite tags attached to baleen whales is still limited at this stage. Generally, data for SDMs of baleen whales obtained through conventional line transect surveys and locations where the target species is absent can be obtained in addition to presence locations. Data obtained by SDMs and satellite tags is complementary information which will improve our understating of the spatial distribution of baleen whales. The results of this study showed that the tagged individuals encountered various environmental conditions while they were moving, though it was difficult to make any conclusion regarding their habitat choice as only two satellite tracking data streams with relatively short time durations were available. It was reported that Bryde's whales in the waters around Madeira Island (southeast North Atlantic) showed diurnal changes in diving depth which was presumable linked to availability of prey [65]. Simultaneous recording of whale movement in four dimensional space (longitude, latitude, depth and time) and prey availability will enhance our knowledge regarding the habitat choices of Bryde's whales.

The mean swimming speed of the individual in 2006 (2.9 km/h) was slower than that of the individual in 2008 (5.5 km/h). The individual in 2006 could swim slowly because it was accompanied by a calf. The breeding season of Bryde's whales in the western North Pacific is long but winter appears to be the peak [66, 67]. It was estimated that gestation and lactation periods last 12 and 6 months, respectively in Bryde's whales as in the case of sei whales [68]. Because only estimated body size was available for the calf, it is difficult to determine the timing of the calving.

This study provides the first information on the movement of Bryde's whales in the offshore western North Pacific in summer and sheds light on an aspect of their life history. However, relatively short transmission durations in this study (13 and 20 days) could not address such a question fully. It was reported that the length of transmissions for humpback whales in the Gulf of Maine was related to the design of the tags [69]. Improvement of the tagging system used in our study should be considered in future study to increase transmission duration. Obtaining more satellite tracking data of Bryde's whales in the area will enhance understanding of the life history and contribute to the conservation and management of this species distributed in that area.

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