Decadal change of feeding ecology in sei, Bryde's and common minke whales in the offshore of the Western North Pacific

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ABSTRACT

Stomach contents from sei, Bryde's and common minke whales sampled by JARPNII cruises in May-October during 2000-2013 (2002-2015 for sei whale) off the Pacific coast of Japan were used to examine yearly trend in prey composition. Stomach content analysis showed that the three whale species are highly dependent on small pelagic fish, in addition to planktonic crustaceans. The change of prey compositions in sei whales among years drastically changed from Japanese anchovy in the early 2000s to Japanese sardine in 2014 and 2015, while *Neocalanus* copepod steadily occurred throughout the years. This decreasing Japanese anchovy synchronized with the catch record of Pacific stocks in Japanese fisheries. Furthermore sea water temperature and school size were different by prey species. Bryde's whale has a more simple prey composition, mostly of Japanese anchovy and euphausiid, and were highly variable among years with no remarkable change during 2000-2013. Prey composition in common minke whales offshore (east of 146°E) showed Japanese anchovy and Pacific saury are the majority species, but the composition differs among years. Japanese anchovy used to be consumed by minke whales around 40°N, but euphausiid was consumed in recent years. These results suggesting a decrease in the amount of Japanese anchovy transported offshore is an important factor to determine the composition of the three baleen whales in the JARPNII study area.

KEYWORDS: SEI WHALES, BRYDE'S WHALES, MINKE WHALES, FEEDING ECOLOGY, JARPNII, NORTH PACIFIC

INTRODUCTION

Offshore of the JARPNII research area is a unique environment under the effect of both cold Oyashio Current and warm Kuroshio Current and this transition region covers most of the JARPNII research area. Eggs and larvae of pelagic fish, such as Japanese anchovy (*Engraulis japonicus*) and Japanese sardine (*Sardinops melanostictus*) are transported by the Kuroshio Current to offshore (Itoh *et al*. 2009; Okunishi *et al*., 2011) and these fish are an important food item for baleen whales, in addition to crustaceans. Feeding of Sei (*Balaenoptera borealis*), Bryde's (*B.edeni*) and common minke (*B. acutorostrata*) whales sampled in JARPNII in this area were reported by the authors (Konishi *et al.*. 2009). Mackerels (genus *Scomber*) are also found in the stomachs of baleen whales from JARPNII study in this offshore area. Because these pelagic fish are also commercially important, there are many studies in catch history (Yatsu *et al.,* 2005; Yonezaki *et al.,* 2014), optimal environment (Takasuka *et al.,* 2007; 2008) and transportation to offshore (Ihoh *et al*., 2007; 2009; 2011). These studies all suggest that the synchronized exchange of favourable environment between Japanese sardine and anchovy caused by climate change, which can be defined by Pacific Decadal Oscillation (PDO) (Mantua and Hare, 2002). In the early 2000s, when sampling of sei and Bryde's whales started in the JARPNII, the sardine population had already collapsed and the anchovy catch had increased (Yatsu *et al*., 2005; Takasuka *et al*., 2008; Itoh *et al*., 2009). The prey of sei, Bryde's and common minke whales also showed abundant Japanese anchovy in the stomach, with rare findings of Japanese sardine. Since PDO fluctuations occur in scale from 15-25 years and 50-70 years (Mantua and Hare, 2002) and continuous sampling in the JARPNII for more than a decade is long enough to explore changes in the feeding habits of sei, Bryde's and common minke whales. Actually, obvious prey changes in sei whales have been observed on board. The main purpose of this study is to observe the decadal change of feeding habits of sei, Bryde's and common minke whales with a general summary by pooling data from all survey years.

METHODS

For the study of basic feeding habits and its decadal change, we used stomach content information from sampled sei, Bryde's and common minke whales with water temperature and position of those whales captured in JARPNII. To show recent changes of stomach contents, we have included data from 2002 to 2015 for sei whales and from 2000 to 2013 for Bryde's whale. Common minke whales are common across Japan's coastal area to offshore areas, and whales have been sampled in different regions and components. Therefore, we used data from 2000 to 2013 at east of 146°E to exclude the effects of prey species specific to near and above the continental shelf and to see change of prey species in offshore areas. The feeding of common minke whales is reported in Tamura *et al*. (2016: SC/F16/JR17). Sampling of whales and stomach content treatment was described in Tamura *et al*. (2016:SC/F16/JR15). In the analyses, comparison of surface water temperature sampled between different prey items, prey composition change with school size and distribution of main prey species fed on by sei whales were described in addition to the prey composition change with years.

RESULTS

Sei whale

Sei whales were sampled mostly from east of 150°E and south of 46°N (Figure 1), between north of the Kurosho extension and just north of the Subarctic Front (see Appendix 3 and Okazaki *et al*., 2016: SC/F16/JR5). The main prey species are *Neocalanus* copepod, euphausiids, Japanese anchovy *Engraulis japonicus,* Mackerels *(Scomber japonicus* and *S. australasicus*) and Japanese sardine *Sardinops melanosticus.* Pacific saury *Cololabis saira* and minimal armhook squid *Berryteuthis anonychus* were also found in far eastern areas. Sei whales were pooled by each main prey species, and surface water temperature where whales were sampled were compared (Figure 2). This result suggests that water temperature where sei whales feed is related to prey species, and feeding of whales on Japanese anchovy and mackerel occur at higher temperatures than copepods and Japanese sardines. The prey composition in occurrence grouped by school size was shown in Figure 3, showing a ratio of copepods likely to be higher in large school sizes. Geographical positions where prey species were fed on by sei whales are illustrated in Figure 4, showing Japanese anchovy and copepods are eaten through wide longitudinal areas while mackerels and euphausiid are fed on in a rather small range. The positions where Japanese sardine was fed on is the most eastern in the survey area overlapping the position of Japanese anchovy and copepod, however those data are from only two years and do not represent the whole distribution. Figure 5 shows a trend of prey composition in the stomach of sei whales sampled during 2002-2015. In the 2000s Japanese anchovy, copepod and euphausiid are major components with few exception in 2005 and 2008. In the years after 2010, mackerels became one of the major prey, which coincided with a decreasing ratio of Japanese anchovy. In the 2014 and 2015 survey years, Japanese sardine was found to be the most dominant prey in 2015 while no Japanese anchovy was confirmed in the stomachs of sei whales. In this year the ration of copepods are also lowest since 2012.

Bryde's whale

Sampling positions of Bryde's whales during 2000-2013 is shown in Figure 6. These positions are located rather south of those in sei whale, and a concentration is seen around 145°E to 150°E. Bryde's whale has more simple prey composition by Japanese anchovy and euphausiid as main prey species. The comparison of Surface water temperature where whales were sampled were pooled by prey species and compared (Figure 7). Overall the temperatures are higher than that of sei whales and we did not find any difference of temperature among prey species. School size of Bryde's whales is relatively smaller than that of sei whales (Figure 8). However the sample size in a school size of four is one and is difficult to find the feature. Geographical positions of prey species fed on by Bryde's whales are drawn in Figure 9. Japanese anchovy was found in a wide longitudinal range and almost covers the entire area where whales were sampled. The number of whales that fed on mackerel is small, however high concentrations were found between 115°E to 160°E. In the case of euphausiids, there is a highly concentrated area where Bryde's whales feed with some smaller spots in the eastern area. The yearly trend of stomach contents in Bryde's whales is shown in Figure 10. The prey composition consists of two species, *i.e*. euphausiid and Japanese anchovy, and oceanic lightfish *Vinciguerria nimbaria* and mackerels were found occasionally. The composition of two main prey species is highly variable among years, and there is no obvious decadal change in the prey composition of Bryde's whales during 2000 to 2013. The higher occurrence of euphausiids is unique for Bryde's whale.

Common minke whale

Prey of common minke whales highly depends on Pacific saury and occurs rather north of sei whales. Prey composition in common minke whales offshore (east of 150°E) showed Japanese anchovy and Pacific saury are the majority species but the composition differs among years. Unlike sei whales, minke whales do not depend on copepods. Because the sampling area and sample size do not have consistency among years in offshore areas, samples were pooled into three terms (2000-2003, 2004-2007 and 2008-2013) and plotted on maps for comparison (Figures 11, 12 and 13). North of the survey area at north of 43°N, Pacific saury is the dominant prey species in all terms with some occasional occurrences of minimal armhook squid (*Berryteuthis anonychus*) and Pacific Pomfret (*Brama japonica*) in most eastern regions. In the years of 2002-2003 and 2004-2007, Japanese anchovy were fed on by minke whales around 40°N while only a few were eaten in the year of 2008-2013. Instead, euphausiid was eaten at this area.

DISCUSSION

This study showed general feeding habits and those decadal changes for sei, Bryde's and common minke whales. Japanese anchovy and mackerels are fed on by sei whales at similar latitudinal and longitudinal areas, but with warmer water temperatures for Japanese anchovy. This difference may be caused by local distributional differences depending on prey species. Sei whales make a larger school size when it feeds on copepods, probably suggesting the sei whale has a function to maximise food intake. In Bryde's whale, euphausiid is a major prey species in addition to Japanese anchovy. From the geographical plots for each prey species, areas that Japanese anchovy and euphausiid were fed on have differences, *i.e*. Japanese anchovy and euphausiid were found from near the Japanese coast to 170°E, however, euphausiid was mostly found at south of 38°N at east of 150°E. This suggests that the feeding habits of Bryde's whales differ in relation to longitudinal sector and have intensive feeding on euphausiid between 145°E to 150°E. Common minke whales showed clear differences with other baleen whales with occurrences at higher latitude to *ca.* 48°N and dependency on Pacific saury.

The results of prey composition changes with years showed that a remarkable prey shift has occurred in sei whales since 2002 to 2015, especially a decline of Japanese anchovy occurrence and incidence of Japanese sardines in the last two years. These changes in Japanese anchovy and sardines coincided with stock abundance estimates of the two fish species (well described by Kishiro *et al*. as Appendix 3 in Tamura *et al.*, 2016:SC/F16/JR17). There was also some variation in the composition, such as no or few occurrence of Japanese anchovy in the early 2000s (2005, 2007 and 2008) and occurrence of mackerels. In Bryde's whales, there was not a clear prey change, probably because of the simple prey composition, and euphausiid was sometimes the highest occurrence throughout the period (2000-2013).

Although both sei, Bryde's and common minke whale distribute throughout the Pacific with a similar latitudinal band (see Jefferson, *et al*., 1993), the high availability of pelagic fish in the JARPNII study area is unique. Therefore, the amount of eggs and juveniles of pelagic fishes transported from the south coastal area and survival and growth seems to reflect the prey composition of the baleen whale species.

In this study, data from the same survey season were pooled. However, prey distribution, physical environment and movement of whales is likely to have a dynamic linkage, therefore feeding information with a shorter time scale was shown in Appendix 1. This is just an example from one month, but this kind of information will be helpful to create a scenario for whale behaviour on a large scale in future studies.

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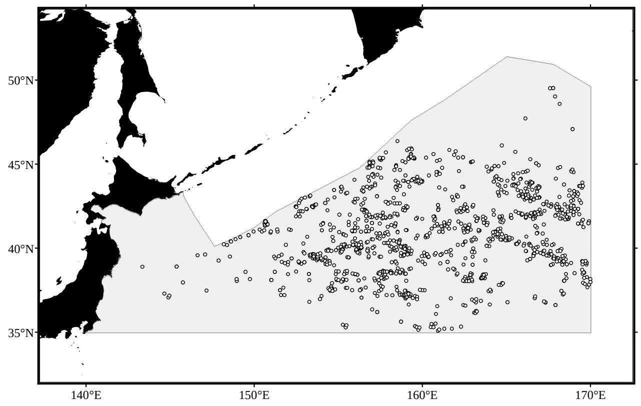
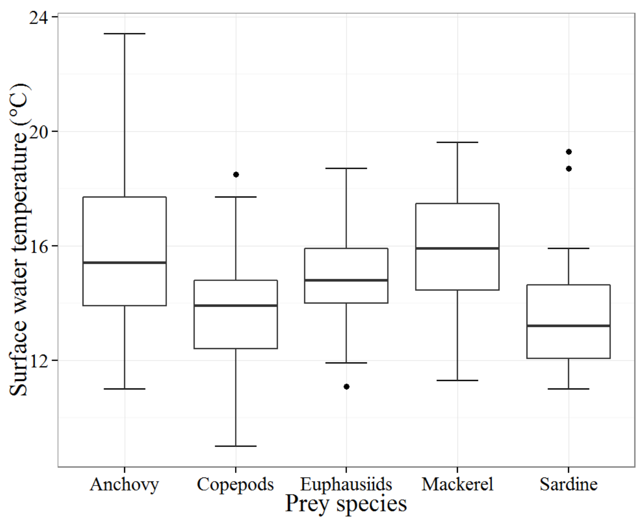


Figure 1. Sighting position of sei whale sampled in JARPNII cruise (2002-2015).



Tukey Contrast test

Copepods - Anchovy <0.001 ***

Euphausiids - Anchovy 0.0298 *

Mackerel - Anchovy 0.9961

Sardine - Anchovy <0.001 ***

Euphausiids - Copepods <0.001 ***

Mackerel - Copepods <0.001 ***

Sardine - Copepods 1.0000

Mackerel - Euphausiids 0.2348

Sardine - Euphausiids 0.0262 *

Figure 2. Relationship between prey species and sea surface temperature where sei whales were caught.

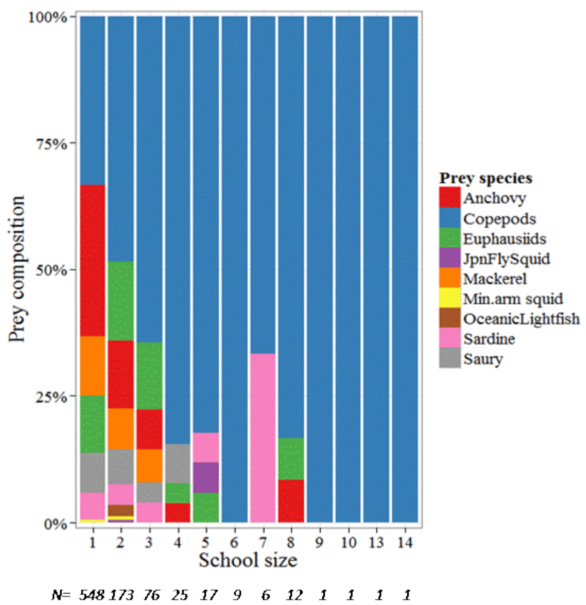


Figure 3. Relationship between school size and prey composition in sei whale.

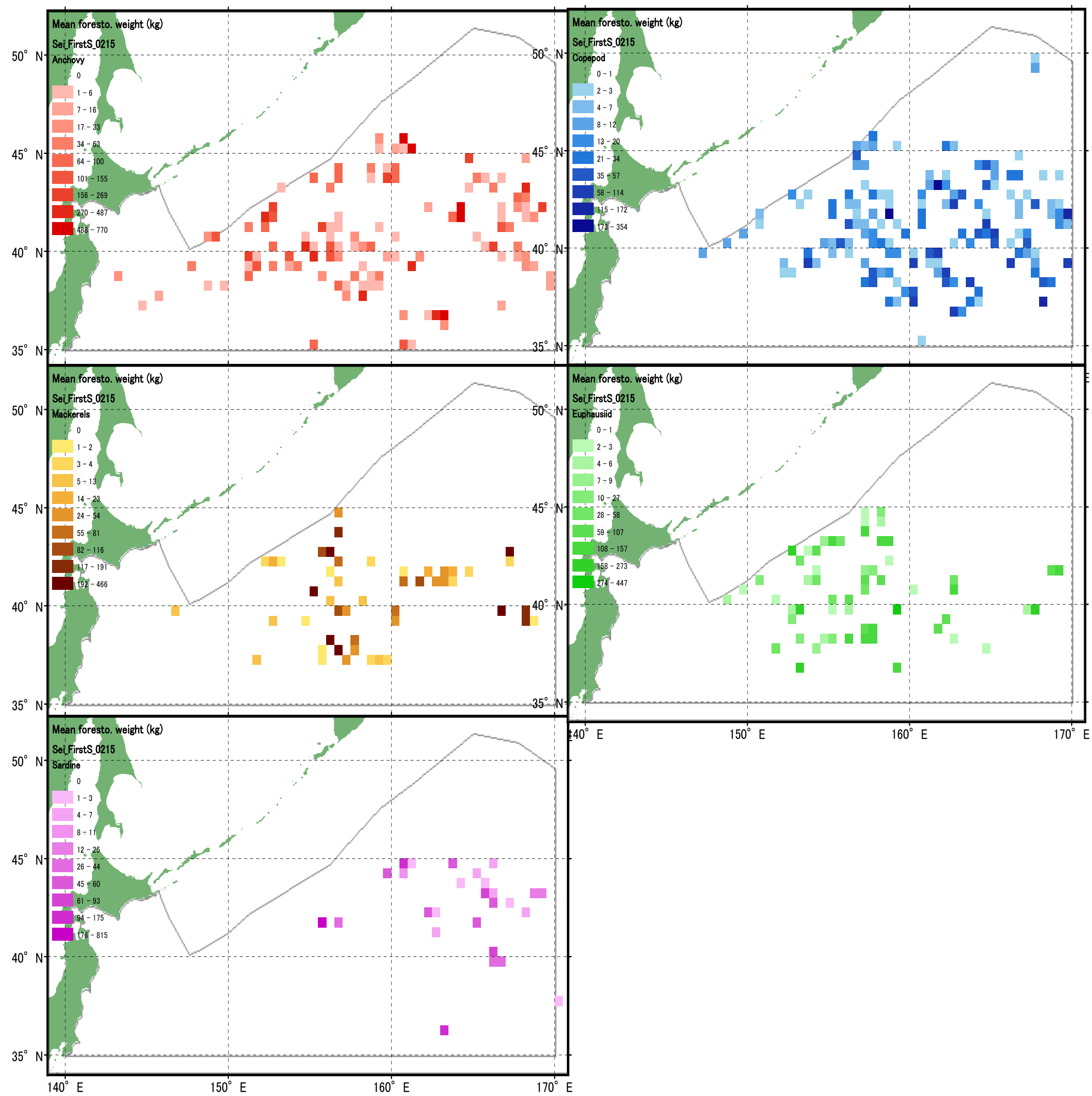


Figure 4. Distribution of prey species fed by sei whales sampled in JARPNII cruise (2002-2015). Mean stomach content weight (kg) by 0.5 degree mesh are illustrated. (upper left Japanese anchovy; upper right copepod; middle left mackerels; middle right euphausiids; bottom Japanese sardine)

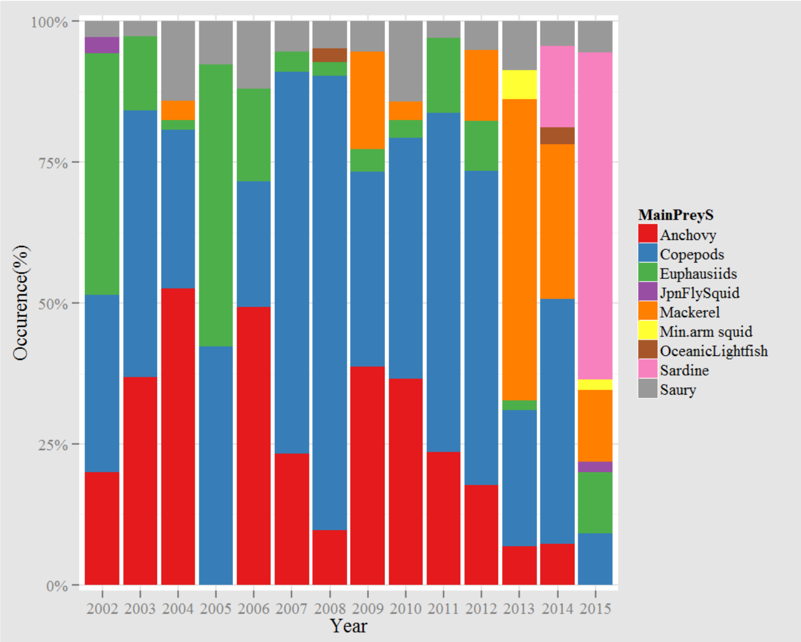


Figure 5. Trend of prey composition in the stomach contents of sei whales during 2002-2015.

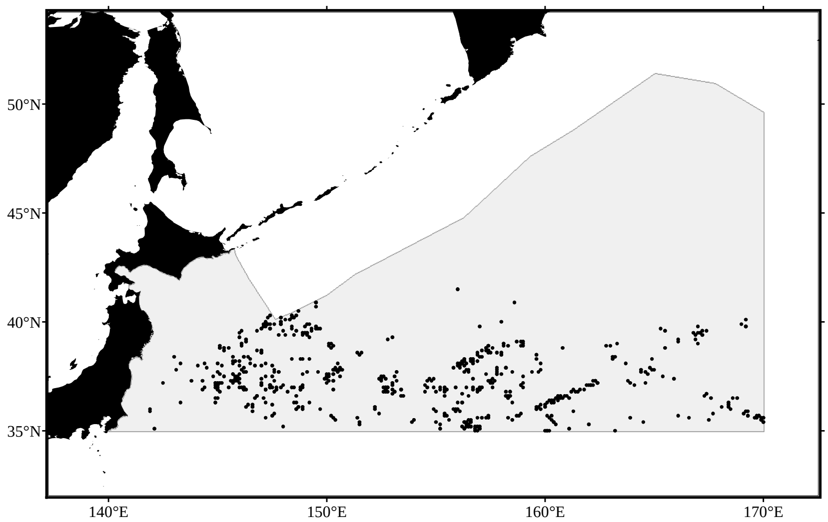


Figure 6. Sighting position of Bryde's whale sampled in JARPNII cruise (2000-2013).

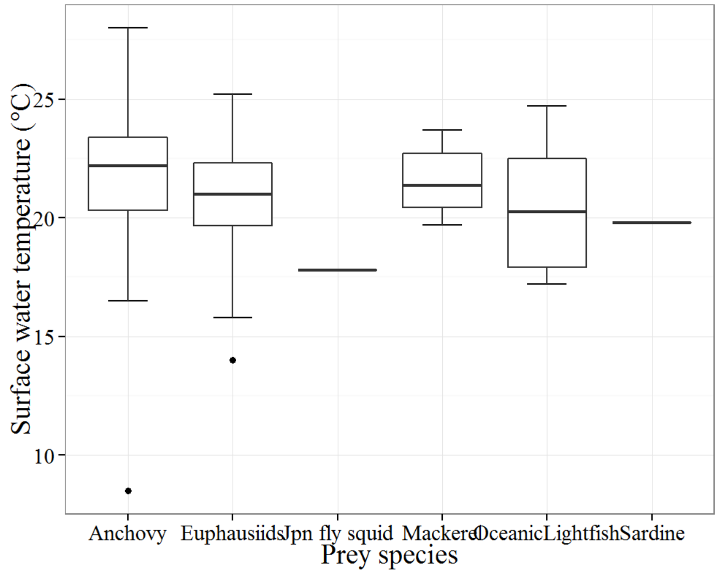


Figure 7. Relationship between prey species and sea surface temperature where Bryde's whales were caught.

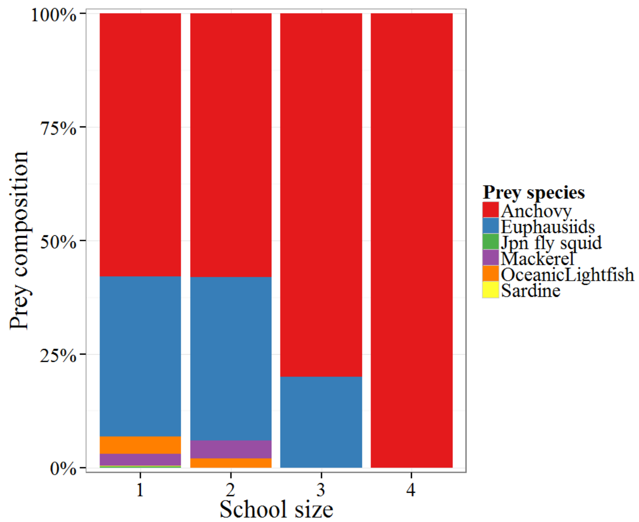


Figure 8. Relationship between school size and prey composition in Bryde's whale.

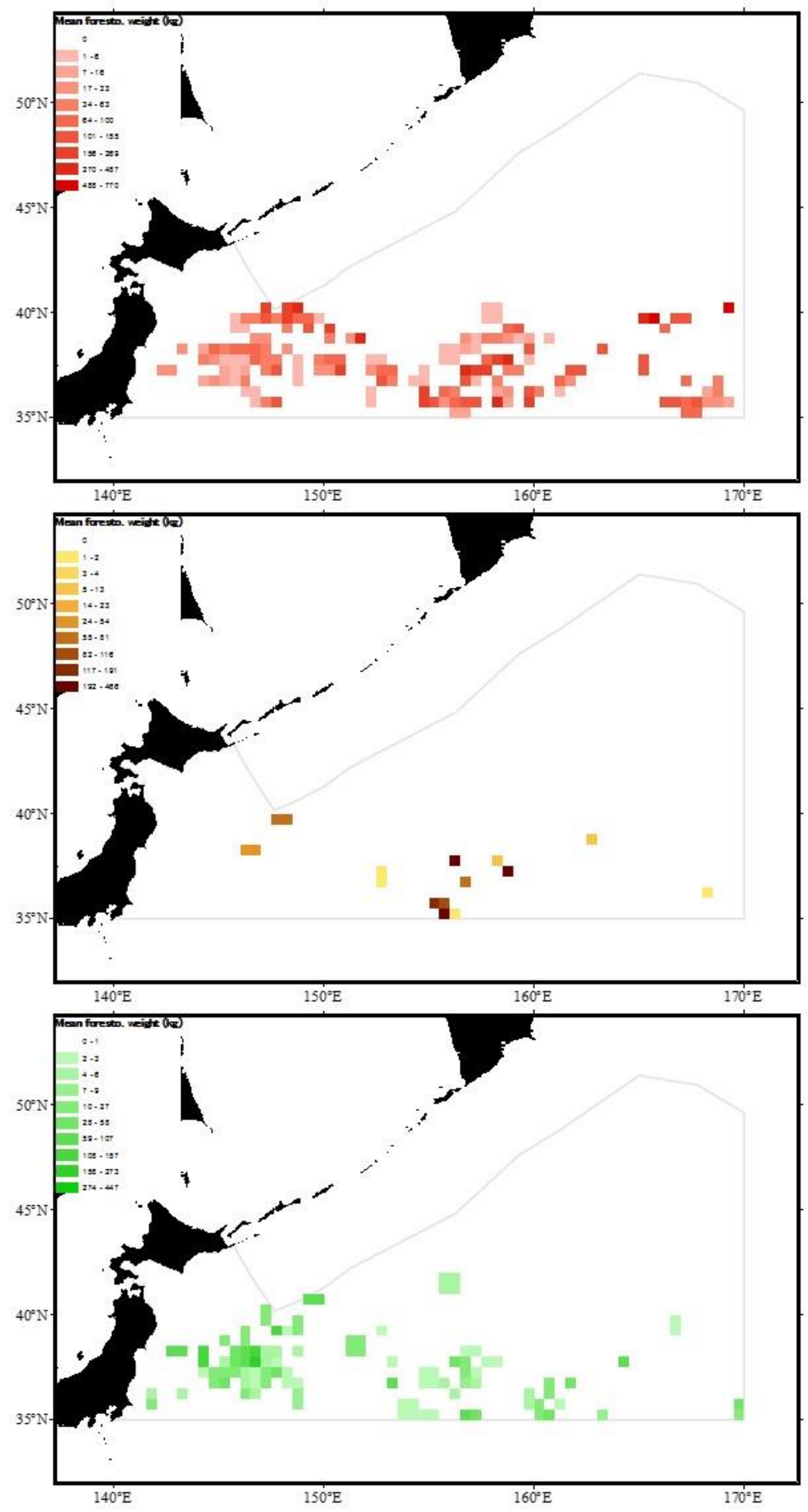


Figure 9. Distribution of prey species fed by Bryde's whales sampled in JARPNII cruise (2000-2013). Mean stomach content weight (kg) per 0.5 degree mesh are illustrated. (upper Japanese anchovy; middle mackerels; bottom euphausiids)

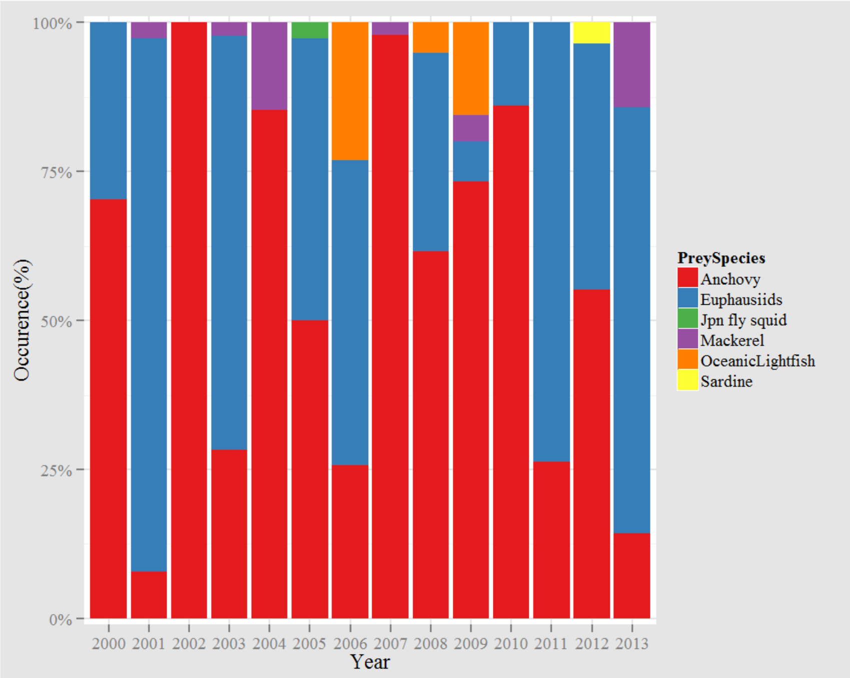


Figure 10. Trend of prey composition in the stomach contents of Bryde's whales during 2000-2013.

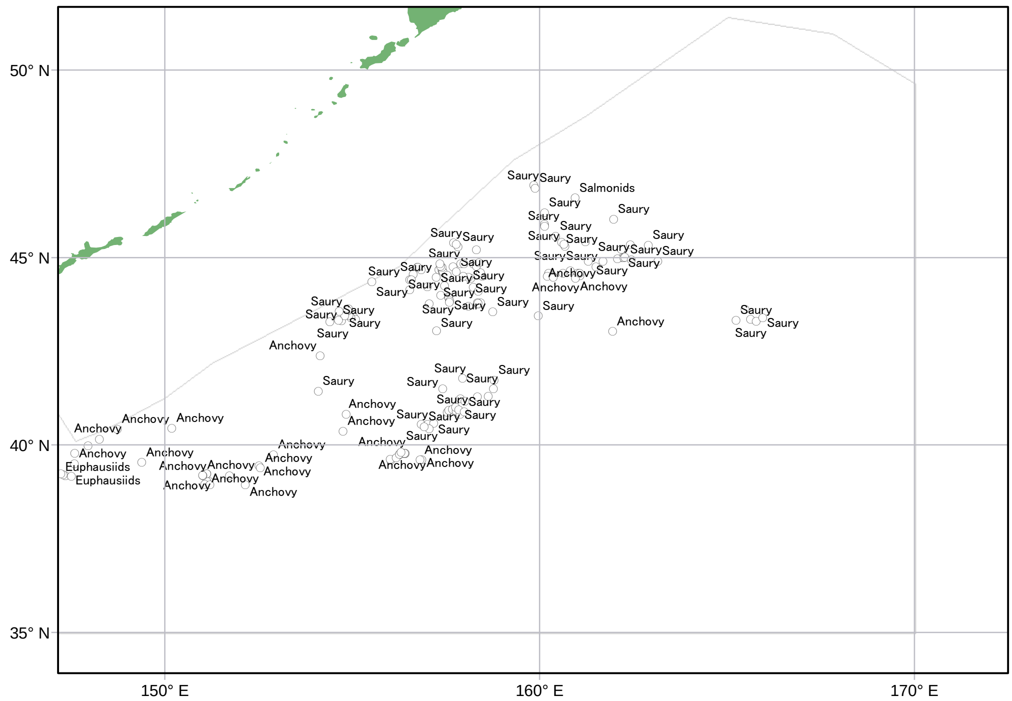


Figure 11. The distribution of prey species fed by common minke whale at east of 146°E during 2000-2003.

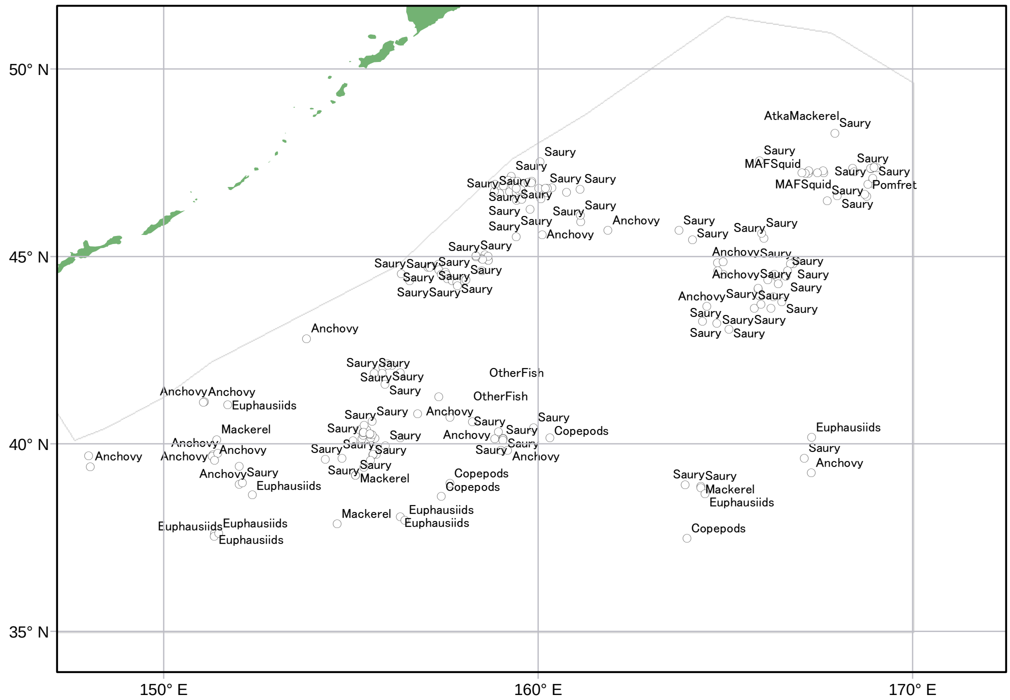


Figure 12. The distribution of prey species fed by common minke whale at east of 146°E during 2004-2007.

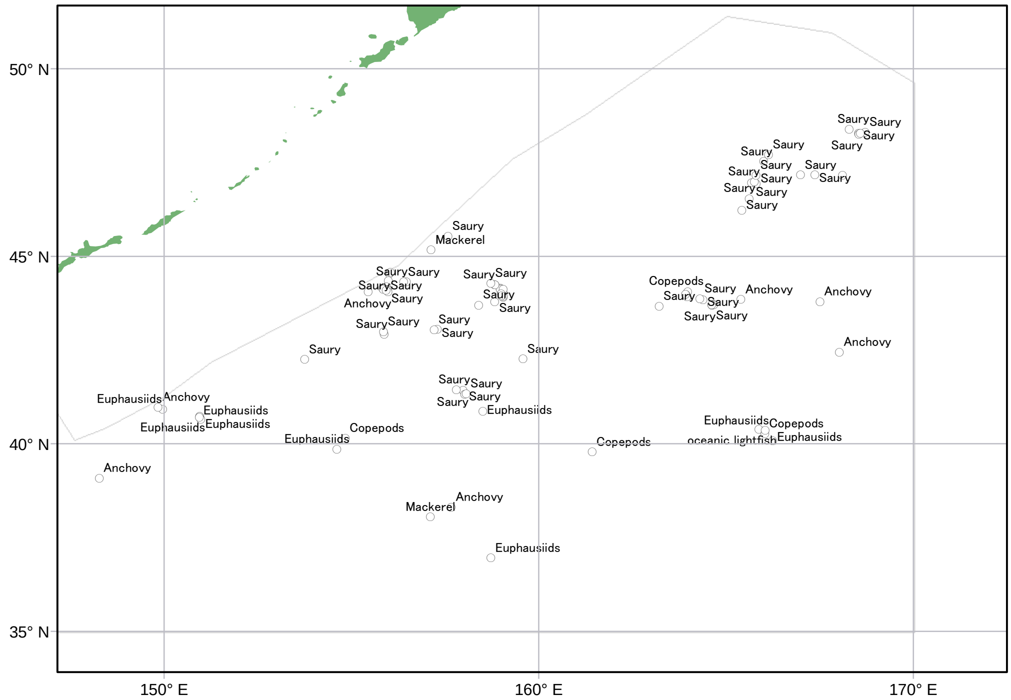


Figure 13. The distribution of prey species fed by common minke whale at east of 146°E during 2008-2013.

Appendix. 1.

Potential dataset for analyses in feeding ecology: Prey species with whale density and environmental factors in the western North Pacific

What factor works in the decision process of prey item for a predator is great concern, however data sometimes need to be pooled in feeding ecology of whales because of the small sample size. Therefore pooled data through survey season were used for trend of prey composition in the main part of this document. However feeding habits in a short time period with environmental factor is maybe preferable for direct interpretation between prey species and environmental factors. This information will be helpful to conduct analyses by integrated dataset from whale sampling, sighting survey and physical environment.

To explore specific feature of prey species in relation to environment with entire survey area but limited time period (a month) as preliminary analyses by overlaying information on a map and "July" was chosen because of available data from every year. When overlaying environmental data with stomach content result, we used sighting and effort data from sighting and sampling vessel (SSV) and sighting vessels (SV) to calculate whale density. Sighting survey procedure is described in Matsuoka *et al*. (2016: JR/F16/JR2). To examine the spatial and temporal variation of whale diets in relation to monthly Chlorophyll a concentration with whale density patterns, Chlorophyll a concentration by 4-km mesh data ware obtained by level-3 data products by NASA Ocean Biology (Sea WiFS) on the satellite images of SST (Aqua MODIS) obtained from Ocean Color Web (NASA Ocean Biology). Then all density and satellite information were averaged with 0.5 by 0.5 degree mesh by ArcGIS 10.2.1 (Esri Inc.), and all plotted for each year (Figure 1). As supplemental information, sighting efforts in July, positions of oceanic fronts are included in Figure 2. To draw oceanographic fronts, sea surface height data were obtained by AVISO webpage. The altimeter products were produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes (http://www.aviso.altimetry.fr/duacs/). To examine positions of oceanic fronts in JARPNII study area, Argo data were used for salinity and temperature profile. These data were collected and made freely available by the International Argo Program and the national programs that contribute to it. (http://www.argo.ucsd.edu, http://argo.jcommops.org). The Argo Program is part of the Global Ocean Observing System. The location of oceanographic fronts were shown in Figure 3.

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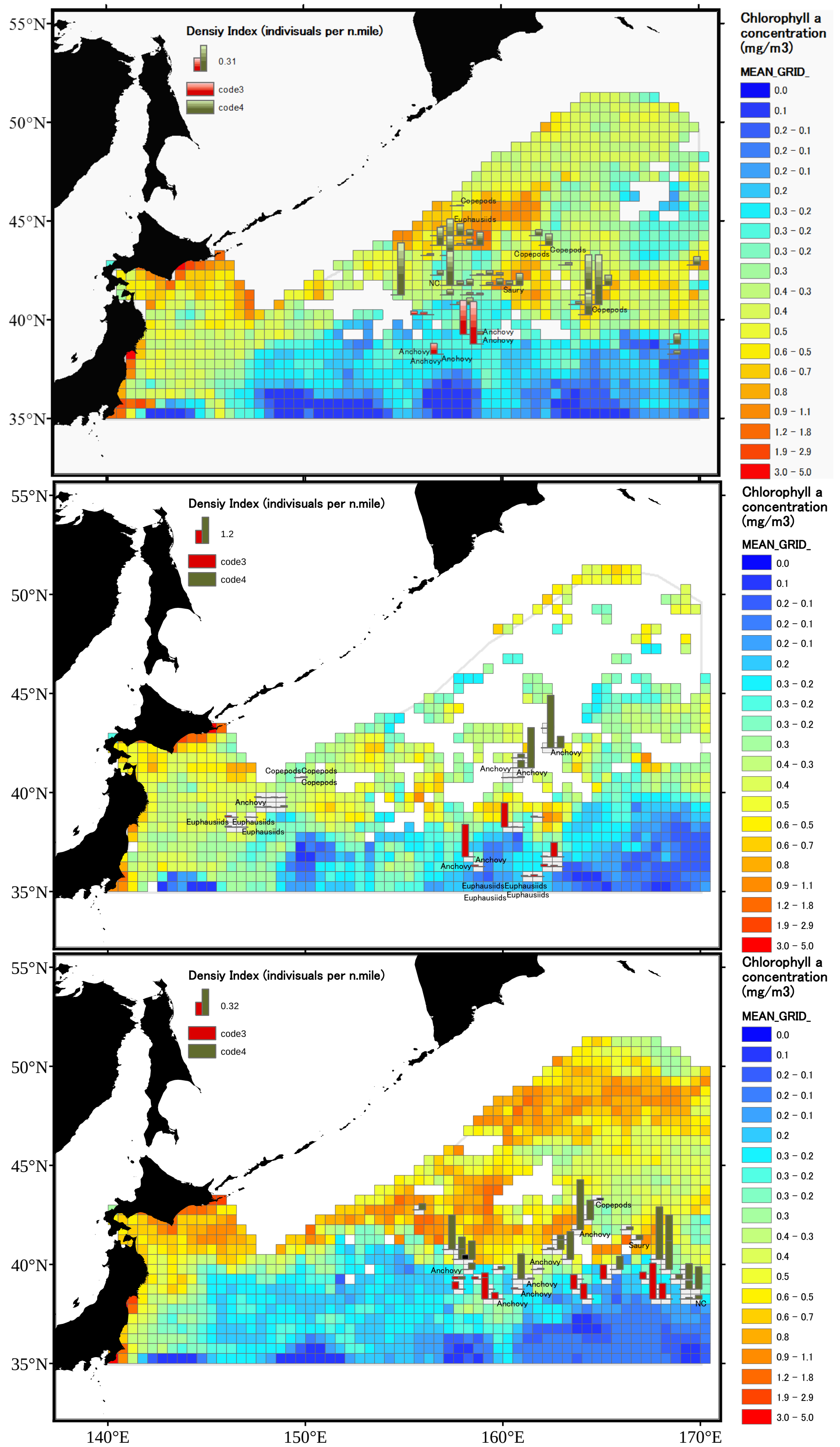

Figure 1. Position, density and prey information of sei, Bryde's and common minke whales in JARPNII 2002-2013 with 5by5 degree meshed average Chlorophyll *a* concentration.in July. Whale Density (DI) was calculated from both (SV and SSV) with efforts per mesh over 5 n.miles and original Chlorophyll *a* is satellite (NASA Ocean Biology (OB). Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Ocean Color Data). (upper: 2002, middle:2003 and bottom:2004 survey years in July). Prey label of "NC" means no content in the stomach.

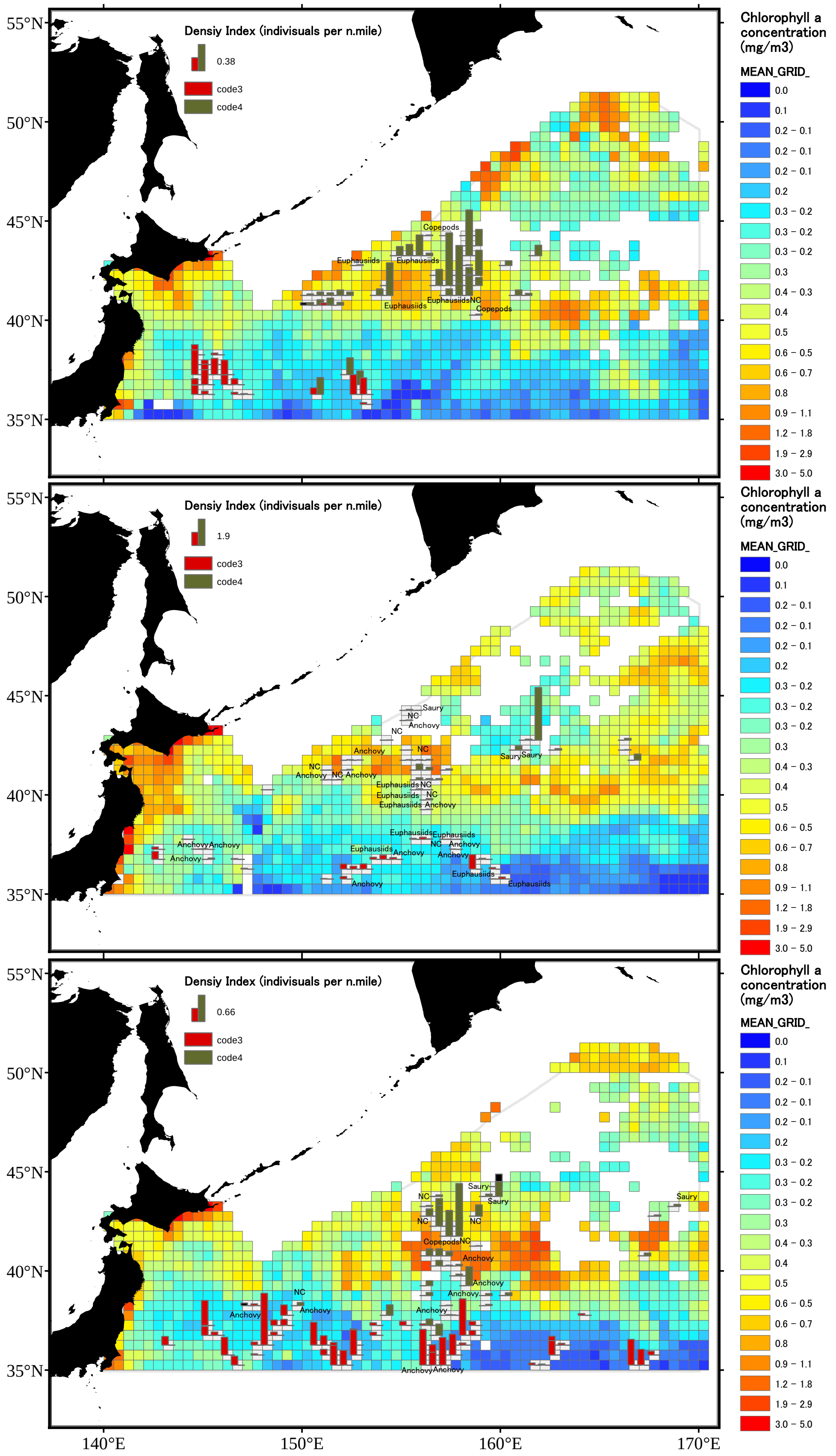

Figure 1. continued. (upper: 2005, middle:2006 and bottom:2007 survey years in July)

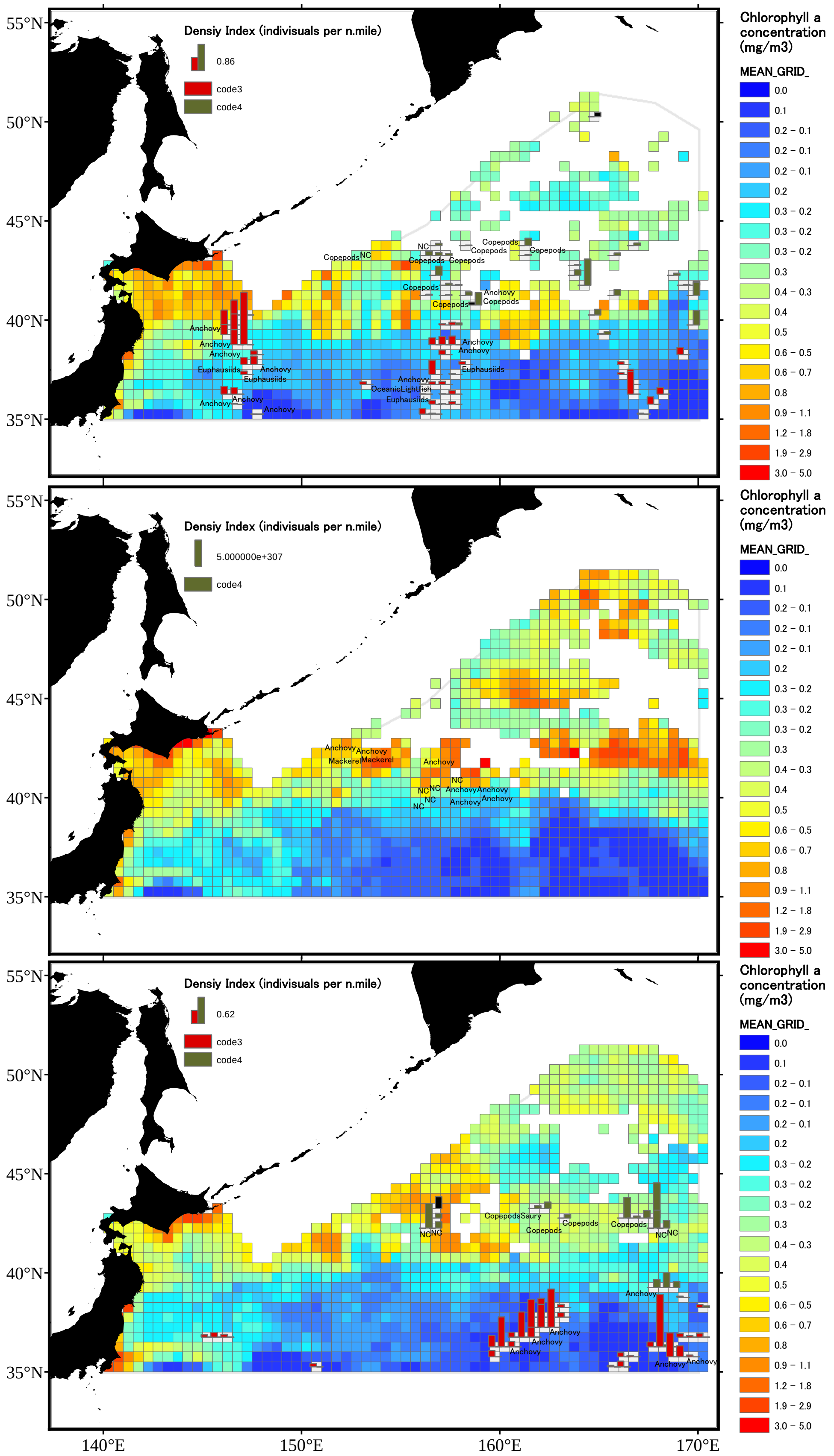

Figure 1. continued. (upper: 2008, middle:2009 and bottom:2010 survey years in July)

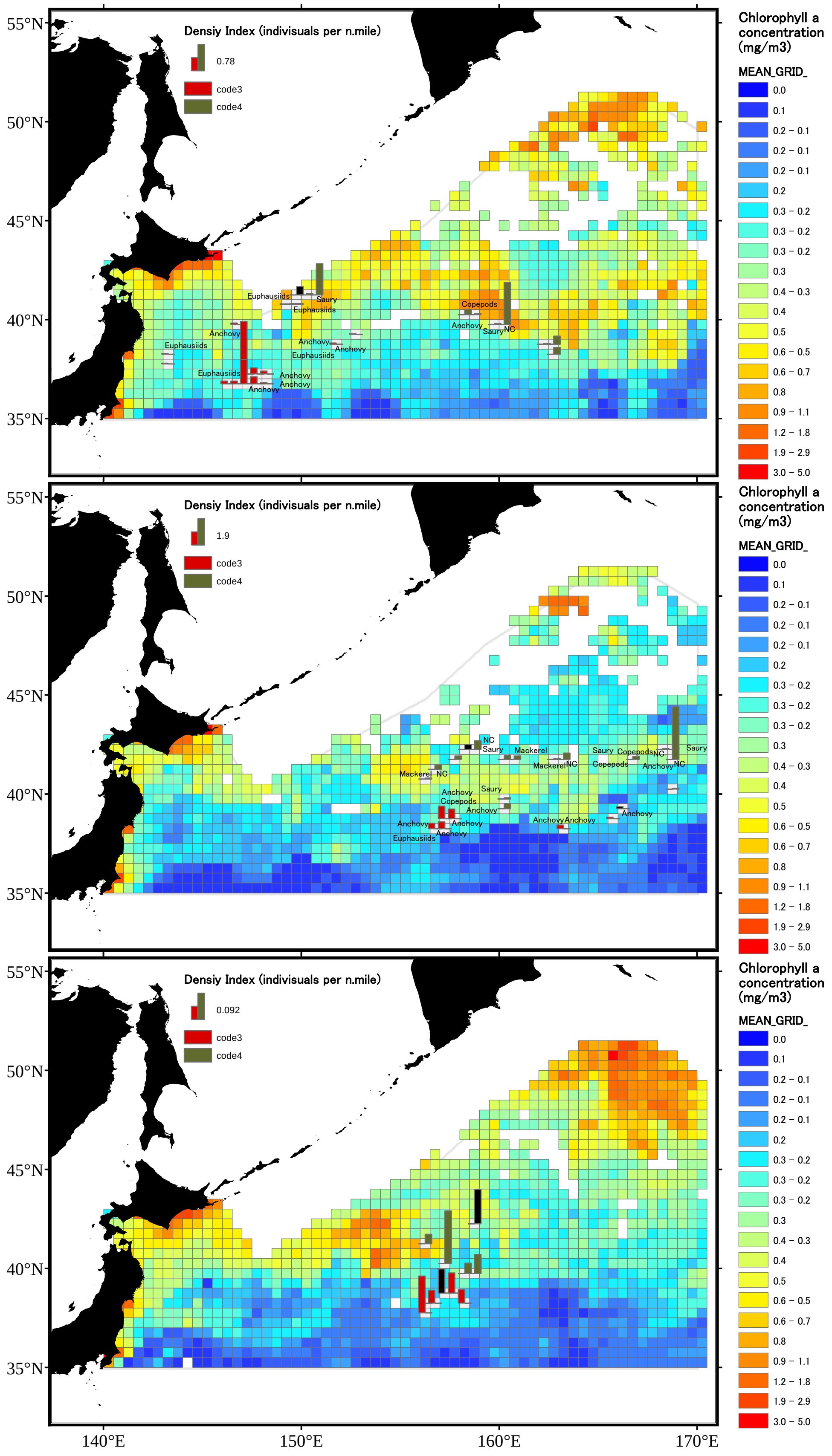

Figure 1. continued. (upper: 2011, middle:2012 and bottom:2013 survey years in July)

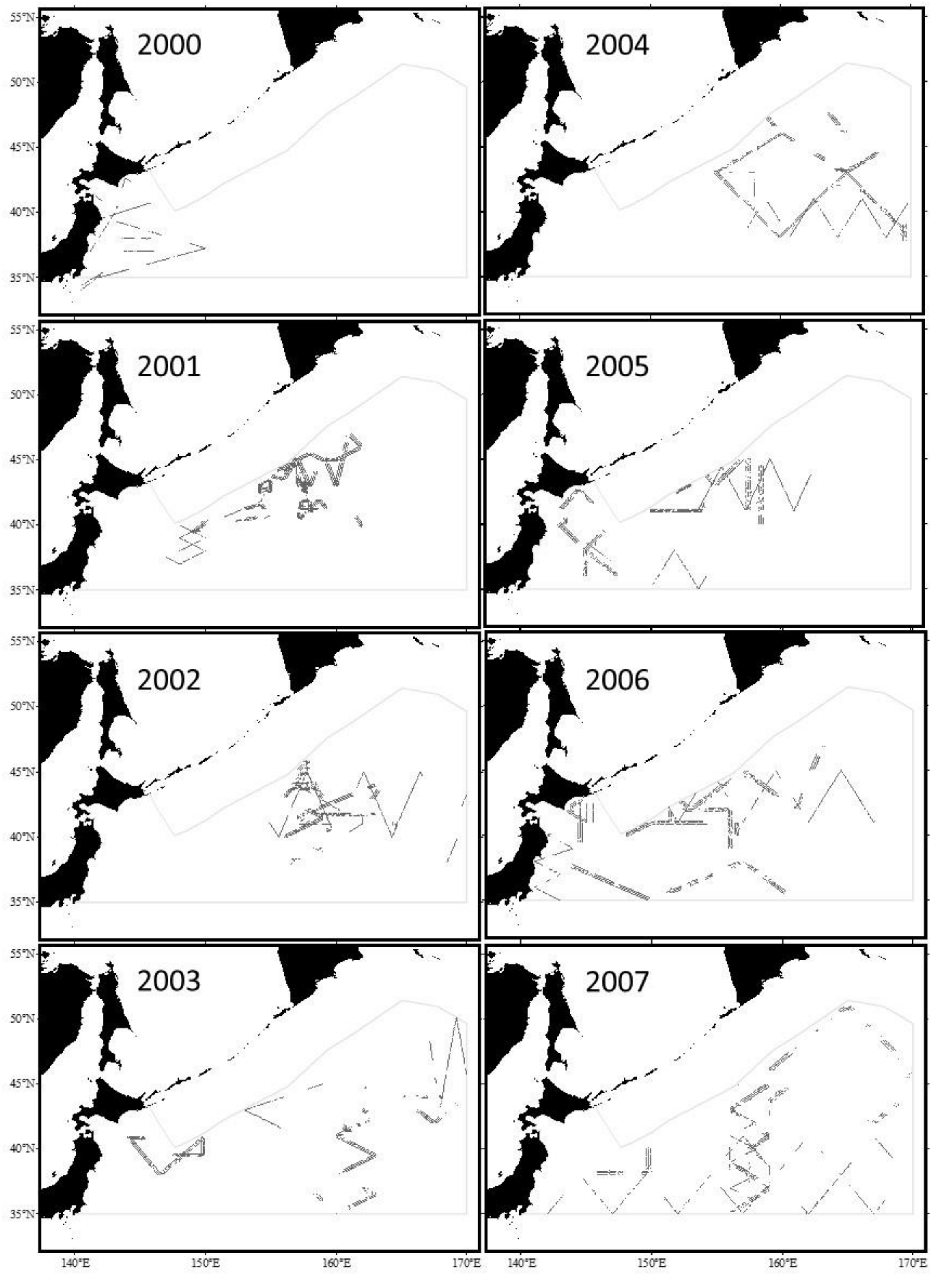

Figure 2. Sighting efforts of sighting vessel (SV) and sighting and sampling vessel (SSV) for each JARPNII survey cruise for each year in July.

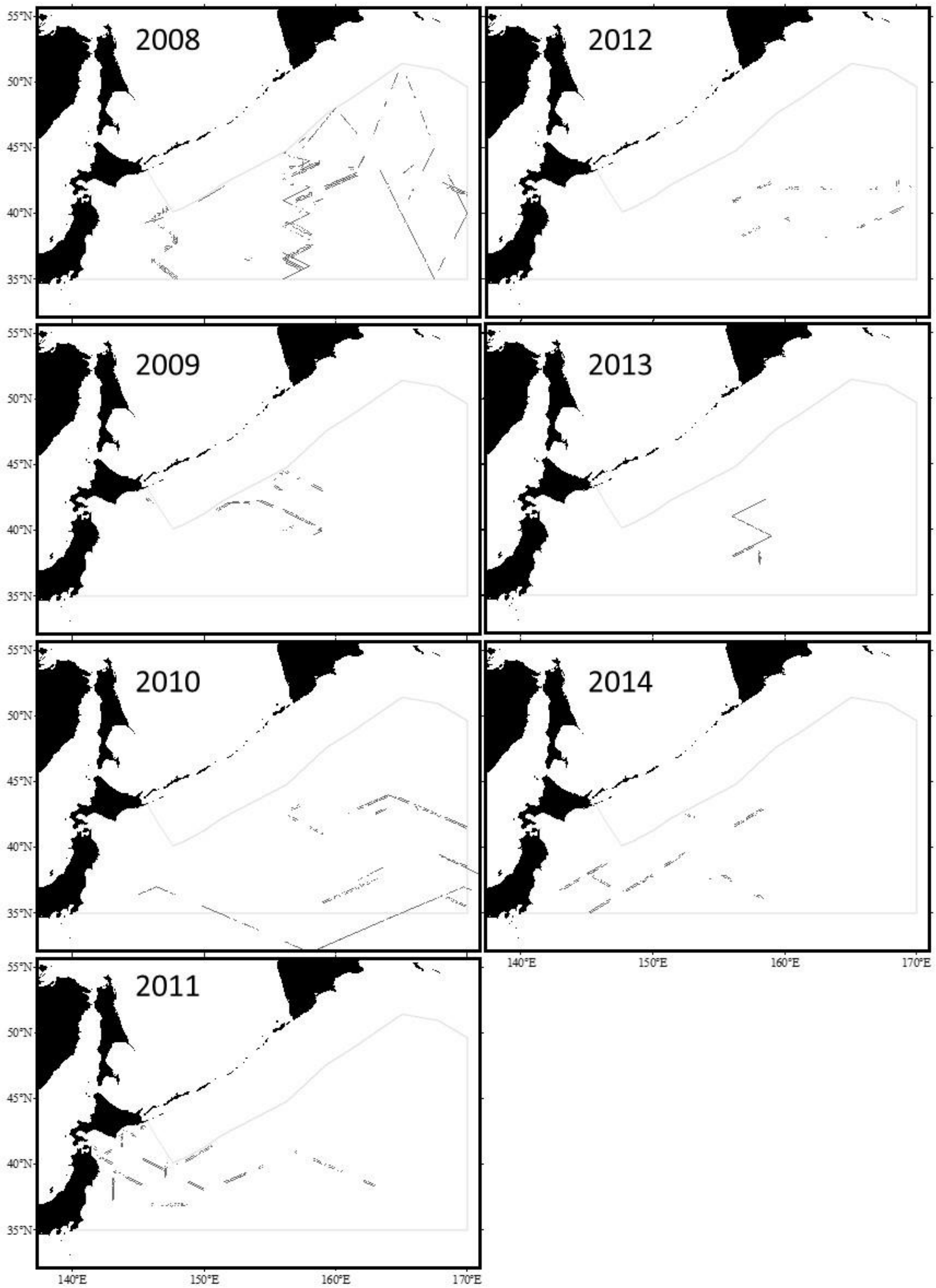

Figure 2. continued.

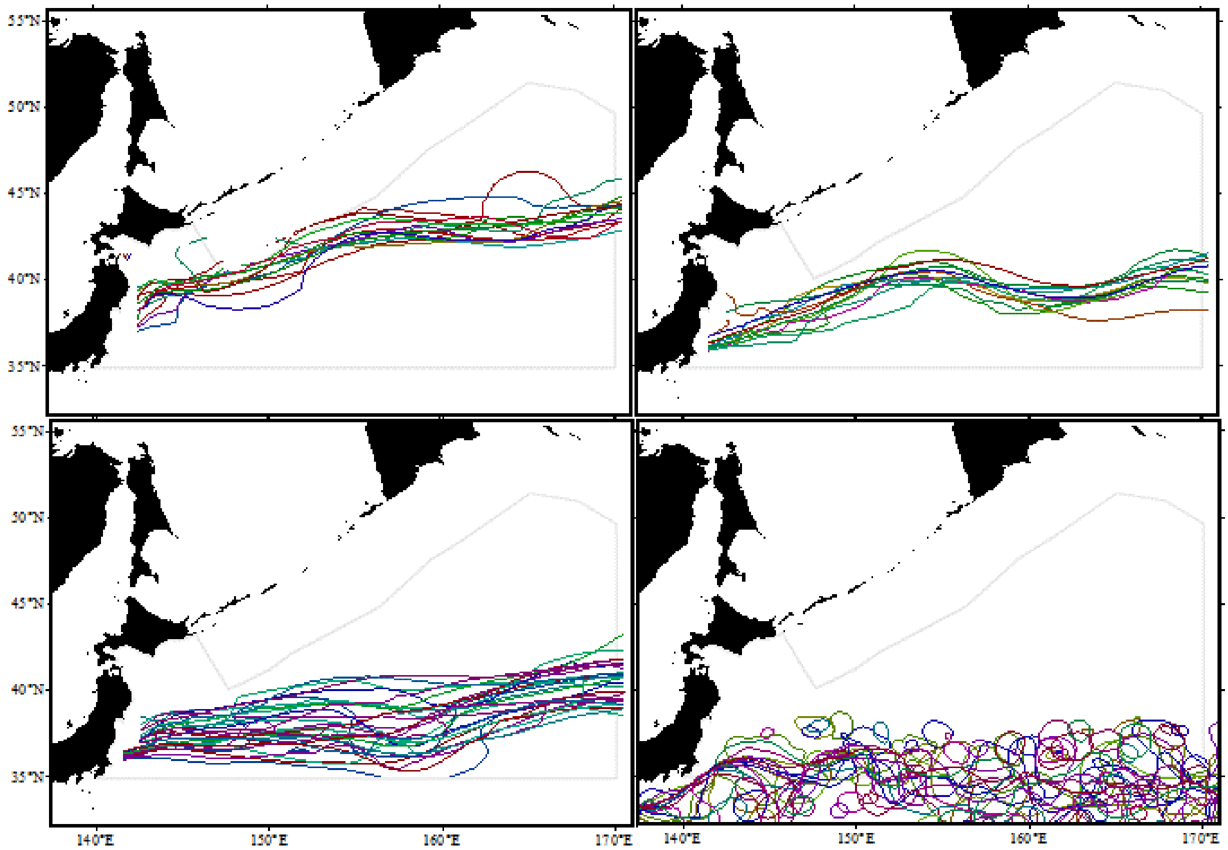

Figure 3. Geographical locations of oceanic fronts at western North Pacific in July during 2001-2013. Original data were Argo float (JAMSTEC) Upper left: 1) Subarctic Front: 4C isotherm at 100m depth (Argo data from JAMSTEC), Upper right: Subarctic boundary: salinity of 34 psu at near surface (Argo data from JAMSTEC), bottom left: 3) Kuroshio extension norther branch, bottom right: 4) Kuroshio extension from sea surface height: (AVISO absolute dynamic topography derived from sea surface height measured by several satellites, AVISO, France, http://www.aviso.altimetry.fr) eddies area also drawn. Detail of oceanographic feature in JARPN I during2000 to 2013 is well described in Okazaki *et al*. (2016: SC/F16/JR5). Definition of boundary was described in Kida *et al*. (2015).

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