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Mare incognita: Adélie penguins foraging in newly exposed habitat after calving of the Nansen Ice Shelf



Seongseop Park^{a,b}, Jean-Baptiste Thiebot^c, Jeong-Hoon Kim^a, Kil Won Kim^b, Hosung Chung^a, Won Young Lee^{a,*}

^a Division of Life Sciences, Korea Polar Research Institute, Incheon, Republic of Korea

^b Division of Life Sciences, Incheon National University, Incheon, Republic of Korea

^c National Institute of Polar Research, Tokyo, Japan

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ABSTRACT

Rapid environmental changes can dramatically and durably affect the animal's foraging behavior. In the Ross Sea (Antarctica), calving of the Nansen Ice Shelf in 2016 opened a newly accessible marine area of 214 km². In this study, we examined the foraging behavior of Adélie penguins from the nearby Inexpressible Island in December 2018, by tracking 27 penguins during their at-sea trips using GPS, depth and video loggers. The penguins mainly foraged within 88.2 \pm 42.9 km of their colony, for 23.4 \pm 6.8 h. Five penguins headed south to the newly exposed habitat along the Nansen Ice Shelf, whereas 22 penguins exploited previously available foraging areas. There was no significant difference in any of the foraging trip or diving parameters between the two penguin groups; however, in the calved region the penguins on Inexpressible Island had explored the newly exposed area after calving. We conclude that the penguins respond to newly available habitat following stochastic environmental events, either through information sharing at the colony, and/or by balancing prey availability per capita across the foraging sites. Considering that this penguin breeding area is under investigation for the establishment of an Antarctic Specially Protected Area (ASPA), the results of this study may provide insights for evaluating the ecological importance of this area and formulating an ASPA management plan for conservation.

1. Introduction

Rapid environmental changes can dramatically and durably affect marine predators (Constable et al., 2014; Trathan et al., 2007; Younger et al., 2016). In polar regions, abrupt changes such as extensive calving events of glaciers and ice shelves may rearrange the local distribution, availability and structure of marine habitats exploited by polar predators, and hence directly influence the animals' foraging behavior. For instance, a large iceberg stranded on penguins' commuting routes to their foraging grounds prevented the penguins to conduct foraging trips during the breeding season (Dugger et al., 2014; Kooyman et al., 2007; Wilson et al., 2016). Recently, a calving from Ross Ice Shelf (in 2000) and series of calving of Larsen A, B, and C Ice Shelf (in 1995, 2002, and 2017, respectively) occurred in the Antarctic coast (Hogg and Gudmundsson, 2017; Lazzara et al., 2008). The ice shelf disintegrations has led to rearrangements of the ecosystem structure, by newly exposing areas that were previously ice-covered (Ingels et al., 2020), and which may affect foraging habitats to marine consumers (Gutt et al., 2011). Ice-shelf retreat or collapse causes the glacier to become thinner more quickly, and freshwater entering the exposed area accelerates vertical exchange between meltwater and deep ocean water, mixing salt, heat and nutrients (Ingels et al., 2020; Truffer and Motyka, 2016).

The Adélie penguin (*Pygoscelis adeliae*) is a predator of krill and fish in the Antarctic marine ecosystem (Clarke et al., 1998; Libertelli et al., 2003). It is one of the most abundant predatory species and is largely distributed around the Antarctic coast (Lynch and Larue, 2014). Since their foraging habits are dependent on sea ice and the related marine environments, they are vulnerable to the recent changes of sea ice (Iles et al., 2020; Le Guen et al., 2018). Simultaneously, they are coping with the environmental changes by responding their reproductive performance (Dugger et al., 2014) or differentiating their foraging efforts according to the sea ice condition (Watanabe et al., 2020). Thus, it is a good model species to monitor the impact of rapid environmental changes on the mesopredators in Antarctica (Ballard et al., 2010;

* Corresponding author. *E-mail address:* wonyounglee@kopri.re.kr (W.Y. Lee).

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Emmerson and Southwell, 2008).

Here, we aimed to investigate the foraging behavior of Adélie penguins near Inexpressible Island, Antarctica. In south of Inexpressible Island, a calving event on the Nansen ice shelf, the Ross Sea, on April 7, 2016, produced two icebergs (totally 214 km² of calving area) and open sea for marine animals, which provided new opportunities to the birds to explore the area (Dziak et al., 2019). Also, Inexpressible Island is one of the places where a special protection status is under consideration due to their ecological importance for penguins and other marine animals (Antarctic Treaty Consultative Meeting in July 2019). The penguin breeding site is included in the management plan for an Antarctic Specially Protected Area (ASPA). Thus, detailed ecological information on penguins, including the number of breeding nests and the foraging areas during the breeding season, is needed for formulating a management plan for the ASPA. Using global positioning system (GPS) loggers, time-depth recorders (TDRs) and video data loggers, we tracked the foraging trips, diving depths and prey capture rates of breeding Adélie penguins.

In this study, we hypothesized that foraging behavior of marine predators would be continuously adjusted to their environment. Thus, with the recent calving event of the Nansen Ice Shelf calving in 2016, we predicted that penguins breeding near the newly exposed areas would take advantage of the increased foraging area available to them to balance predation pressure across sites. We also anticipated that exploring newly available habitats may incur additional costs to the penguins, associated with less optimal tactics in exploiting previously unknown habitats.

2. Methods

2.1. Study site and field study

Inexpressible Island ($74^{\circ}54'$ S, $163^{\circ}39'$ E, area: 30.9 km^2) is a rocky island located in the Ross Sea, Antarctica (Fig. 1). There are approximately 25,000 Adélie penguin breeding nests, which were counted by aerial photographs in 2017 and 2019 (MOE, 2020) (see supplementary Table S1 for the population trend of Inexpressible Island).

Field study was conducted on December 15, 2018 at the Adélie penguin colony located in Seaview Bay, on the west side of Inexpressible Island. Nests with two guarded chicks were monitored for a shift of the attending partner: the leaving partner was then captured away from its nest and fitted with the following loggers. First, a GPS logger (model F3G 133 A, SIRTRACK, New Zealand; dimensions $63 \times 24 \times 22$ mm, mass 31 g, sampling rate 30 s) and a time-depth recorder (TDR, model LAT, 1810, Lotek Wireless, Canada; dimensions $36 \times 13 \times 10$ mm, mass 9 g, sampling rate 1 s) were attached to 34 penguins. We attached loggers to the mid-line dorsal feathers of the penguins using Tesa tape for fixing (Wilson et al., 1997; Wilson and Wilson, 1989).

In addition, three of the studied birds were equipped with a video data logger, also attached along the dorsal mid-line but in front of the other loggers, near the scapular joint, for a clear field of view (video logger model and dimensions; for detailed methods, see Choi et al., 2017). Video loggers recorded data continuously for two to 3 h, and recording started with a 3 h delay timer after deployment (DVL400M065, Little Leonardo, Tokyo, Japan; dimensions: $68 \times 20 \times 14$ mm, mass 29 g). One of the three recorded penguins did not have any foraging behaviors in the video-recordings so that it was not included in



Fig. 1. Overview of the study site. (A) This study was conducted at Inexpressible Island in Victoria Land along the Ross Sea (left). (B) Bathymetry and coastline represented on Landsat 8 OLI/TIRS C1 Level-1 satellite image provided by USGS EarthExplorer. The bathymetry contour of GEBCO 2014 data is shown on December 16, 2015, before the Nansen Ice Shelf calving event occurred (upper right). (C) Cloudless satellite image near this study after the collapse of the Nansen Ice Shelf (the white dashed line) is indicated on the map on December 08, 2016 (lower right).

the analysis. Two of the recorded penguins include foraging during the video-recordings (138 min of recording in ID04 and 190.4 min in ID32). The detailed information of recordings are represented in Table 2. All handling times were within 10 min, and the total mass of the attached loggers was below 40 g, corresponding to 0.9% of the average body mass of the deployed penguins (4.4 kg). When the loggers were attached, no aberrant behavior was observed in the handled individuals, and it was visually confirmed that all penguins headed safely to the coast. Upon returning from their at-sea foraging trips, the studied penguins were recaptured, the loggers were retrieved, and the bill depth, bill length, and body mass were measured. The bill measurements were used to determine the sexes considering the sexual size dimorphism (Kerry et al., 1992).

All GPS and TDR units were retrieved from the 34 penguins. However, in three cases the loggers malfunctioned, in three other cases only half of the at-sea trip was recorded, and no movement was recorded in one penguin: these were all excluded from the analysis. Therefore, a total of 27 foraging round trips from 27 individuals (11 males and 16 females) were used to examine the at-sea distribution and foraging location of the penguins.

2.2. Tag tracking data analysis

The collected GPS coordinates were linearly re-interpolated at 1s intervals to match the TDR data, using Ethographer (Sakamoto et al., 2009) in Igor Pro 6.32 (WaveMetrics, OR, USA). All spatial analysis and mapping were performed in ArcMap 10.8 (ESRI, CA, USA). Time spent at the colony was excluded from the foraging trip. Using these GPS data we calculated the foraging trip parameters: round trip duration, maximum distance reached from the nest, and total distance traveled per trip. Using the time-depth data collected from each individual, we calculated the dive parameters: maximum dive depth, mean dive duration, and mean dive depth.

The Nansen Ice Shelf edge before the calving event was marked as a polyline based on the Landsat 8 OLI/TIRS C1 Level-1 satellite image provided by USGS EarthExplorer (website: https://earthexplorer.usgs.gov/). This polyline was subsequently overlayed on the post-calving image (Fig. 1). The General Bathymetric Chart of the Oceans 2020 Grid (GEBCO, 15 arc-second resolution, downloaded from website: https://www.gebco.net/data_and_products/gridded_bathymetry_data/) was used to infer the bathymetry at each diving point. Dives where subsequently separated between those performed in shallow habitats (bathymetry shallower than 100 m), and those performed where the seafloor was deeper.

2.3. Statistical analysis

The penguins' at-sea foraging parameters (horizontal and vertical) were examined as a function of the exploited marine area: open sea versus area newly exposed after the calving of the Nansen Ice Shelf. All statistical analyses were performed using the program R version 3.6.3 (R Core Team. R foundation for statistical computing, Vienna, Austria. 2020). Differences in the foraging trip parameters (trip duration, maximum distance, and total movement distance), maximum dive depth and number of dives (total number of dives in each individual, the number of dives in shallow areas, and the proportion of dives in shallow areas) were examined as a function of the foraging area using generalized linear models (GLMs) in the R package "stats" (Bolar, 2019). Variables with repeated measures within individuals (dive duration and dive depth) were analyzed using generalized linear mixed models (GLMMs) in the R package "lme4" (Bates et al., 2020), accounting for the penguins' individual IDs as a random effect. Wald test in GLM and likelihood ratio test in GLMM were performed in order to verify the significance of the statistics. We used Fisher exact test for estimating sexual differences in foraging directions (open sea vs. newly exposed area).

3. Results

3.1. Foraging trip and dive parameters

Among the 27 studied penguins, 22 headed towards the open water in the east and southeast of the island, while five others moved to the south and exploited the marine area newly exposed after the calving of the Nansen Ice Shelf (Fig. 2). There were no differences between the sexes for the heading directions (8 males and 14 females among the 22 individuals to the east and southeast, and 3 males and 2 females to the new area; Fisher exact test, p = 0.37). Also, there were no significant differences between the sexes in all foraging parameters (see supplementary Table S2 for the foraging trip parameters and statistics for the comparisons).

The penguins' foraging trip lasted 23.4 ± 6.8 h (mean \pm SD, all the same notations below use this format), and extended up to 30.2 ± 17.5 km from the nest (total horizontal distance: 88.2 ± 42.9 km, Table 1). There was no significant difference in trip duration, maximum distance reached, total distance traveled, according to the area exploited by the penguins (Table 1) Similarly, dive metrics did not differ significantly between the two penguin groups (mean dive duration: 106.9 ± 13.0 s, mean dive depth: 32.9 ± 7.8 m, maximum dive depth: 85.0 ± 9.9 m, number of dives per trip: 480.5 ± 164.9).

However, the penguins which foraged in the newly exposed area near the Nansen Ice Shelf edge performed 42.1% of their dives in the shallow habitats (less than 100 m, see Fig. 1 to the bathymetry near Inexpressible Island), markedly more than did the penguins that foraged in the open sea (1.4% of shallow dives; Table 1).

Dives reaching depths of 5–20 m accounted for approximately 49% of all performed dives, while those reaching 50–70 m accounted for approximately 21% of the dives (Fig. 2).

3.2. Video recording results

Video data was available from the three instrumented individuals; however, only two of them foraged at sea during the video recording time. Both these penguins foraged eastwards (see supplementary Figure S1 for the map showing where the video data were recorded along the tracks). Footage covered a total of 92 dives, and over 3 h underwater (Table 2), across which 2267 prey captures were visible (or presumed, from the observed penguin's typical head movements). The captured prey that were visible on the videos consisted predominantly of krill (Antarctic or ice krill but not distinguishable), and one unidentified prey (fish-like shape) (Fig. 3). Presence of other penguins in the image field was remarkably frequent (40.2%, 52 dives of all 92 dives). In 23 dives, there was a single individual of a conspecific; in 13 others two individuals were noted, and in one dive up to three different individuals were visible.

4. Discussion

In this study, we examined the foraging behavior of Adélie penguins on Inexpressible Island. Our results showed that approximately two years after calving of the Nansen Ice Shelf, nearly one fifth of the Adélie penguins studied from Inexpressible Island were already exploiting the newly available foraging habitat.

The general direction of the penguins' predominant foraging trips tracked in 2018 at Inexpressible Island (east and southeast) was similar to those observed at the same colony 18 years earlier (Table 1; Olmastroni et al., 2020). In December 2000, the foraging trips lasted longer however, likely because more pack ice was present then than in December 2018, hence slowing down the commuting penguins (Watanabe et al., 2020) (see supplementary Figure S2 for the satellite images on December 18, 2000 and December 18, 2018). Most importantly, from the foraging trip and dive parameters measured in the two penguin groups in our study (eastward to the open sea vs. southward to the



Fig. 2. Foraging trips of 27 Adélie penguins breeding at Inexpressible Island (marked with a yellow star). (A) 22 penguins headed eastward and in Terra Nova Bay. (B) Five penguins headed southward and visited the newly exposed area after the Nansen Ice Shelf calving. Light gray indicates land, and the black double line indicates the Nansen Ice Shelf edge before calving. (C), (D) Proportion of dives in relation to dive depth of 27 Adélie penguins breeding on Inexpressible Island. 22 Eastward penguins (C) and 5 Southward penguins (D) were marked in different gray colors. Proportion of dive expressed as mean \pm SE through the gray squares. Diving deeper than 85 m, which is less than 1% in total, has insufficient samples and is excluded from the figure. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

calved region), it is remarkable that there was no apparent cost associated with the exploitation of a new foraging environment. Thus, our results contrast with the previous studies which examined how environmental stochastic events modified the foraging environment of penguins associated with increased commuting costs (Dugger et al., 2014; Ropert-Coudert et al., 2015; Watanabe et al., 2020). While such stochastic events had negative effects on the provisioning rates of these predators by obstructing their routine foraging routes, associated with increased commuting costs, our study showcased an increase in the foraging area available to the penguins, at apparently no extra cost for them, after the calving of Nansen Ice Shelf.

Newly exposed areas could be combined with micronutrients through meltwater, making them known for being ecologically and chemically rich places (Bertolin and Schloss, 2009; Liniger et al., 2020). The ice shelf calving event exposes both benthic and pelagic areas as ice-free, which could not be accessed in the form of an ice shelf. In the Larsen A and B Ice Shelf disintegration regions, ice sheet collapse increases pelagic productivity and enriches the organic supply to the benthos as it causes benthopelagic coupling (Ingels et al., 2020). Studies have also shown the rapid adaptation and exploitation behavior of

marine predators to newly exposed Larsen areas (Gutt et al., 2011). Unlike the penguins tracked in the same population 18 years ago (Olmastroni et al., 2020), in this study, some penguins were headed to the newly exposed Nansen Ice Shelf area. These results suggest that the new area may provide Adélie penguins on Inexpressible Island with an opportunity for predation in the regions that are newly enriched by the changing ocean environment created by the ice shelf break-up. The five penguins that headed southward performed on average 42.1% ($\pm 18.2\%$, SD) of the dives in the shallow habitat (water depth < 100 m), suggesting the possibility of encountering prey near the seafloor as well as pelagic prey. In the Ross Sea area, krill and fish are known to be the main prey items for Adélie penguins (Ainley et al., 1998; Clarke et al., 1998). Especially, in our study population, the main prey items are reported to be krill (72.8% on average) and fish (16.0%; mostly Antarctic silverfish) with a small proportion (less than 10%) of amphipods and squids (Olmastroni et al., 2020). Our video-recordings also supports that dominant prey items are krill and fish. Thus, it is expected that krill and fish are sufficiently distributed in the new foraging habitats after calving so that the penguins might be attracted to this area.

Given the presumed benefit for the penguins in exploiting this newly

Table 1

Foraging trip parameters (horizontal movement and diving) from the 27 Adélie penguins tracked at Inexpressible Island. Eastward and southward birds did not show significant difference in foraging trip and dive parameters, but dives in the shallow water (depth < 100 m) were highly dominant in southward individuals to the Nansen Ice Shelf (33.1% of all dive) compared to the ones in eastward individuals (2.7% of all dives). Mean \pm SD values are used for average parameter results. GLM means generalized linear models and W is the wald test for the statistical significance. GLMM means generalized linear mixed models and birdID is set to random effect. LRT is the likelihood ratio test for the statistical significance (see 2.3. Statistical analysis).

| | Total | Eastward | Southward | Statistics | | | |
|--------------------------|-----------|---------------------|-----------------------------------|------------|-------|-------|--|
| | | | (to the Nansen ice shelf) | χ^2 | р | Model | |
| n | 27 | 22 | 5 | | | | |
| Foraging trip parameters | | | | | | | |
| Trip | 23.4 | $\textbf{23.4} \pm$ | 23.7 ± 4.2 | 0.009 | 0.93 | GLM & | |
| duration | \pm 6.8 | 7.4 | | | | W | |
| (hour) | | | | | | | |
| Maximum | 30.2 | $30.9~\pm$ | $\textbf{27.4} \pm \textbf{5.6}$ | 0.17 | 0.68 | GLM & | |
| distance | ± | 19.3 | | | | W | |
| (km) | 17.5 | | | | | | |
| Total | 88.2 | 89.2 \pm | $\textbf{83.8} \pm \textbf{16.3}$ | 0.067 | 0.8 | GLM & | |
| distance | ± | 47.2 | | | | W | |
| (km) | 42.9 | | | | | | |
| Dive parameters | | | | | | | |
| Mean Dive | 106.9 | 106.5 \pm | 108.8 \pm | 1.0 | 0.31 | GLMM | |
| Duration | ± | 13.5 | 11.7 | | | & LRT | |
| (s) | 13.0 | | | | | | |
| Mean Dive | 32.9 | $32.9~\pm$ | 33.1 ± 7.8 | 0.13 | 0.72 | GLMM | |
| Depth (m) | \pm 7.8 | 8.0 | | | | & LRT | |
| Maximum | 85.0 | $\textbf{85.9} \pm$ | $\textbf{81.0} \pm \textbf{7.4}$ | 0.002 | 0.96 | GLM & | |
| Dive | \pm 9.9 | 10.3 | | | | W | |
| Depth (m) | | | | | | | |
| Number of dives | | | | | | | |
| Total no. Of | 480.5 | 486.9 \pm | $\textbf{452.2} \pm$ | 0.19 | 0.67 | GLM & | |
| dives per | ± | 180.1 | 71.8 | | | W | |
| individual | 164.9 | | | | | | |
| No. Of dives | 38.7 | 6.0 ± 5.0 | 182.6 \pm | 80.0 | < | GLM & | |
| in shallow | ± | | 67.0 | | 0.001 | W | |
| habitat | 74.8 | | | | *** | | |
| Percentage | $9.0 \pm$ | 1.4 ± 1.3 | $\textbf{42.1} \pm \textbf{18.2}$ | 63.0 | < | GLM & | |
| of dives in | 17.7 | | | | 0.001 | W | |
| shallow | | | | | *** | | |
| habitat | | | | | | | |

Table 2

Summary of the information visualized from the video data (n = 2 individuals, both foraged eastward). Mean \pm SD values are used for average parameter results.

| Variable | Penguin ID04 | Penguin ID32 | Combined information |
|--|--|--|----------------------|
| Recording start time Recording time Recording end time | Dec 16, 2018 06:16:39 Dec 16, 2018 | Dec 15, 2018 15:09:52 Dec 15, 2018 | |
| | 08:34:38 138 min | 18:20:17 190.4 min | |
| First dive time in record | Dec 16, 2018 06:15:59 | Dec 15, 2018 15:09:01 | |
| Last dive time in record | Dec 16, 2018 08:34:04 | Dec 15, 2018 18:20:03 | |
| No. Of dives on video | 44 | 48 | 92 |
| Recording time underwater (m) | 87.5 | 96.6 | 184.1 |
| Average dive duration (s) | 119 ± 12 | 118 ± 29 | 119 ± 23 |
| Total number of capture events | 849 | 1418 | 2267 |
| Average number of capture events per dive | 19.3 ± 9.7 | 29.5 ± 17.1 | 24.6 ± 14.9 |
| No. Of observations of conspecifics | 36 | 16 | 52 |
| % of dives with conspecifics visible | 54.5 | 27.1 | 40.2 |

available area, it may be wondered why only a minority of the studied penguins visited this sector. One hypothesis may be that the knowledge on the existence of this newly exposed habitat had not fully spread yet among individuals (Bonner and Farge, 1980; Galef, 1992; Laland and Hoppitt, 2003). Information sharing on favorable foraging spots is likely to spread eventually in colonially-breeding birds, through vocal communication (Choi et al., 2017). Indeed, colonial assemblages are presumed to have a role in maximizing the exploitation by conspecifics of unevenly-distributed food sources (Ward and Zahavi, 1973). Another hypothesis is that the numbers of studied individuals exploiting each site may reflect the respective quality of each site, in terms of the food availability (the ideal free distribution hypothesis, Fretwell, 1969). If the penguin distribution follows the ideal free distribution model, the individuals are assumed to have food resources-dependent strategies and a perfect knowledge of their environment to select their foraging sites. Considering that our results showed a skewed result toward the eastward open ocean, the food availability of the east foraging site would be much higher than that of the south. These fine adjustments observed in the penguins' foraging tactics, in line with a dynamic environment, are likely to be one mechanistic element supporting the stability and capacity of resilience of their populations (See supplementary Table S1 for the number of pairs) against the stochastic environmental events. In line with the food availability hypothesis, the proximate ecological factor driving penguins to newly exploit this newly available habitat might be to minimize potential competition, compared to the habitat predominantly exploited by this population, and reach balanced levels of available food per capita across sites. Indeed, the extremely high co-occurrence of conspecifics during dives (as seen in videos: >40% of dives, on average) suggests high levels of potential intraspecific competition across the main habitat. Previous video studies in penguins showed far lower observation rates of conspecifics (2% of total dives in Magellanic penguins Spheniscus magellanicus, Gómez-Laich et al., 2018; <0.1% in Macaroni penguins, Sutton et al., 2021), including in Adélie penguins at other sites (authors' unpublished data). However, the prey capture rates by the video-equipped penguins seemed very high in our study in the Eastward habitat (over 12 krills/min) compared to other studies in Adélie penguins (e.g. 5 krills/min, Watanabe and Takahashi, 2013). This suggests that prey supply was high in this main foraging area, and thus that intraspecific competition levels may not be limiting the penguins' provisioning there. In the absence of data on prey capture rate in the south, we cannot exclude either that provisioning rate was at least equivalent there for the minority of penguins that chose to exploit this newly available habitat. Therefore, the hypothesis that reaching a balanced food availability per capita would explain why only a minority of penguins exploited the newly available habitat, remains plausible but to be formally tested.

5. Conclusion

Overall, our findings detail the foraging habitats used by Adélie penguins from Inexpressible Island and show how a habitat newly uncovered by the calving of an ice shelf may create new foraging opportunities for predators. Further research is needed to clarify which mechanisms support and/or limit the exploitation of the newly available habitats by penguins, including information sharing, prey type, and per capita prey availability among predators. In addition, our results provide detailed information about the variability of the foraging area of penguins from Inexpressible Island, which further contributes to our understanding of the ecology of this region. Such progresses are key to support ASPA management decisions, such as recognizing a status of special protection, currently under consideration for this site.

Credit author statement

Seongseop Park: Formal analysis, Writing – original draft, Jean-Baptiste Thiebot: Writing – original draft, Jeong-Hoon Kim: Project



Fig. 3. Images of prey captured while diving and footage when conspecific is observed. Images A and B are footage of prey presumed to be krill swarm and an unidentified fish-like shape, respectively. Images and C and D are conspecific photographs observed during the foraging dive and sea surface, respectively.

administration, Kil Won Kim: Funding acquisition, Hosung Chung: Funding acquisition, Project administration, Won Young Lee: Conceptualization, Formal analysis, Investigation, Writing – original draft, reviewing and editing, Supervision

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Ethical approval

This study was conducted by permission from Korean Ministry of Foreign Affairs and Trade (certificate number: ILAD-4566 [2019.11.21], according to the current laws of Republic of Korea ('Act on Antarctic Activities and Protection of Antarctic Environment').

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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