FLIGHT ALTITUDES OF CHICK-REARING RHINOCEROS AUKLETS *CERORHINCA MONOCERATA* MEASURED BY GPS LOGGER

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ABSTRACT

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Alcids generally fly at low altitudes (below 5 m) over the sea but may occasionally fly higher in certain areas, which may put them at risk of collision with turbine blades in offshore wind farms. We used GPS loggers to investigate the location and altitude of flying Rhinoceros Auklets *Cerorhinca monocerata*. They typically flew at low altitudes averaging < 1 m but flew higher (> 20 m) when returning the last 5–10 km to their colony, which was located at an elevation of 120–130 m above sea level. Thus, the region over which Rhinoceros Auklets fly highest may vary, depending on the location and elevation of their breeding sites. Therefore, it is important to consider spatio-temporal flight altitude patterns when assessing their collision risks with offshore wind turbines.

Key words: elevation of colony, collision risk, alcid, offshore wind farm, seabird

INTRODUCTION

The ecological impacts associated with the development of offshore wind farms are of public concern, and seabird collisions with wind turbines are among the issues considered (Desholm *et al.* 2006). Thus, seabird collision risk should be assessed in potential wind farm construction areas (Bradbury *et al.* 2014). For accurate risk assessment, knowledge of seabird locations, behavior, and flight altitude is essential (reviewed by Thaxter *et al.* 2015). To date, flight altitude of seabirds has usually been investigated by radar from a fixed station or by observation from survey vessels (Cook *et al.* 2012). For example, Ainley *et al.* (2015) used at-sea data collected from large research vessels, which can remain on the ocean under a wide range of wind and sea conditions. They reported that as the wind increased, petrels (other than storm petrels) and albatross increased flight height significantly and increased the ratio of gliding to flapping. In contrast, alcids did not change behavior all that much relative to wind speed, and they generally flew at low heights above the sea. In recent years, spatio-temporal variations in flight altitude have also been investigated using continuous position and altitude data recorded by global positioning system (GPS) loggers or barometric pressure loggers (Corman & Garthe 2014, Cleasby *et al.* 2015).

Alcids are a major component of seabird communities in the Northern Hemisphere and are potentially threatened by offshore wind farm developments. Flight altitude studies indicate that alcids rarely fly at altitudes that incur collision risks (Krijgsveld *et al.* 2011, Johnston *et al.* 2014). However, Sanzenbacher *et al.* (2014) reported that the Marbled Murrelet *Brachyramphus marmoratus* flew at 93–98 m above ground level inland near the coast, which would clearly put them at risk of collision. Therefore, investigations of spatio-temporal flight altitude patterns must be conducted to accurately assess Alcidae collision risks when planning for the construction of wind farms.

In this study, we used GPS loggers to investigate the flight altitude and location of a medium-sized alcid, the Rhinoceros Auklet *Cerorhinca monocerata*, during foraging trips from the colony on Teuri Island (44°25′N, 141°19′E; Fig. 1) in northern Hokkaido, Japan. Wind conditions are suitable there for wind farm operations, potentially placing the birds at risk. On Teuri Island, the auklets nest at elevations of 120–130 m above sea level; thus, they must fly to at least those altitudes to arrive at and depart from their breeding sites. Using GPS data, we were able to demonstrate the elevation, location, and timing of auklets flying at high altitudes, particularly around their breeding site.

METHODS

We conducted fieldwork during May and June of 2018 and 2019 near the Akaiwa Observatory (130 m above sea level) on Teuri Island, 28 km west of Haboro, Hokkaido, Japan. We captured 37 adult Rhinoceros Auklets in their burrows (120–130 m altitude) and attached GPS loggers (CatLog Gen2 Patch Antenna, Perthold Engineering, Germany; 160 mAh or 300 mAh battery; 42×23×13 mm; 12.9–15.6 g) to their mantle feathers using waterproof heat-shrink tubing, TESA tape (4651, tesa®, Germany), and superglue. We recaptured 11 of 13 individuals in 2018 and 11 of 24 individuals in 2019 after 3.5 ± 2.9 days of deployment (min–max: 1–10 days, $n = 22$) to recover the loggers. One of the loggers retrieved in 2019 malfunctioned owing to a leak. We programmed 35 of the 37 loggers to record at five-minute intervals in 2018 and 2019. In 2018, we programmed two loggers to record at 15-minute intervals but found that the interval was too long to analyze flying behavior; thus, we excluded these loggers from our analyses but used them for assessment purposes only (Appendix 1). Overall, we analyzed data from 19 individuals on 36 foraging trips. To investigate the effect of logger deployment on the study individuals, we weighed the birds to within 5 g both before and after deployment, and we also measured the body mass growth
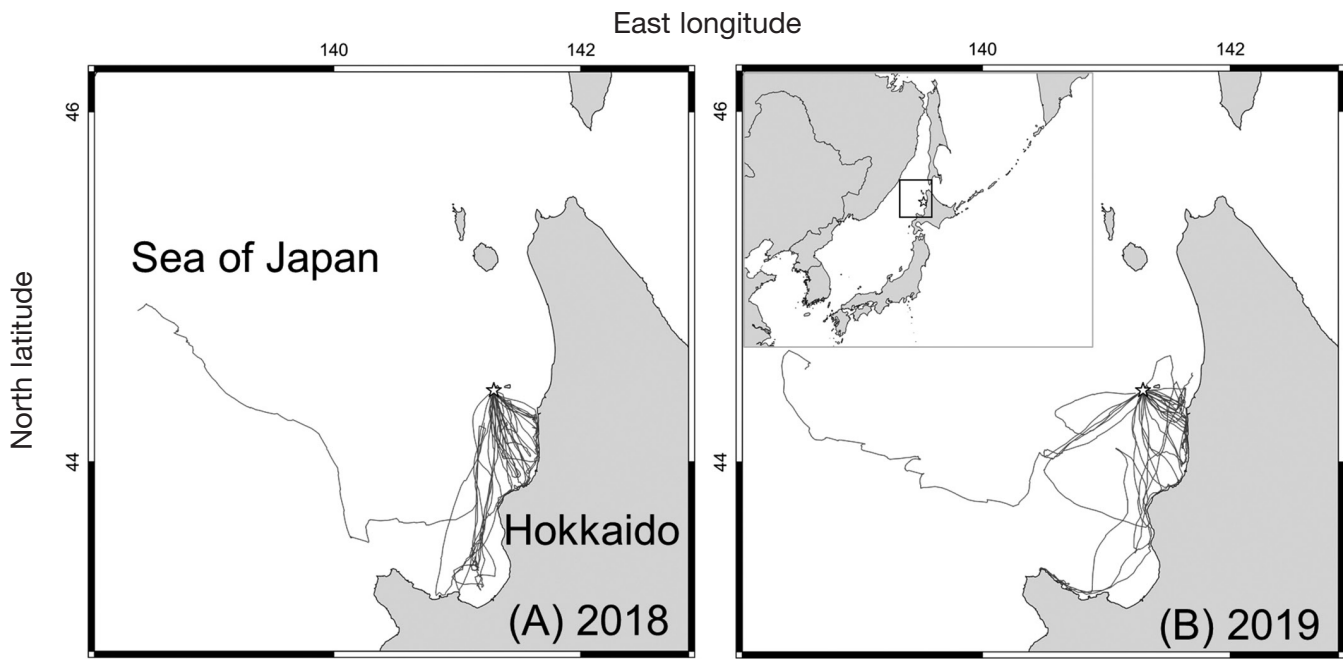
Fig. 1. Foraging trip tracks by Rhinoceros Auklets *Cerorhinca monocerata* breeding on Teuri Island (star) in (A) 2018 and (B) 2019. Complete and incomplete trips are shown. The location of the study area is indicated by the square on the map of Japan (inset).

of their chicks (see Appendix 1 for a detailed impact assessment of logger deployment). Research permits were granted by the Japanese Environmental Agency (1801131, 1902122), the Agency for Cultural Affairs (29-4-1838, 30-4-691), and the Institutional Animal Care and Use Committee. The latter is based on the Regulations on Animal Experimentation (ID: 16-0054) set by the National University Corporation Hokkaido University.

During chick rearing, parents forage at sea during the day and return to feed their chicks at night. We defined a foraging trip from the breeding site as the period from departure at dawn until arrival at dusk the following night or later. The records were sometimes interrupted before the bird returned to its burrow due to battery exhaustion (i.e., records showed incomplete trips). We measured trip duration as the time in hours between departure and return. We recorded the

maximum linear distance travelled from the colony in kilometers, along with the total distance moved (defined as the sum of distances between consecutive points in kilometers) for each complete trip. We calculated the averages for each year and for both years (Table 1).

We calculated flight speed from the distance and time that elapsed between two consecutive points. A speed filter of 80 km·h⁻¹ (22.22 m·s⁻¹) was applied to remove unrealistic records (Wilkinson *et al.* 2018). The speed of movement at sea followed a distinct bimodal distribution (Fig. 2). We used the valley of the bimodal distribution (6 m·s⁻¹) as a movement threshold and assumed, following Zavalaga *et al.* (2010), that the lower speeds indicated birds that were resting on the sea surface or diving and the higher speeds indicated birds that were flying. Some studies have used the momentary speed measured by GPS loggers to classify the state

TABLE 1
Foraging trips made by Rhinoceros Auklets *Cerorhinca monocerata* breeding on Teuri Island, Japan, recorded using GPS loggers during the chick-rearing season in May and June of 2018 and 2019ᵃ

	2018	2019	Total
Number of individuals	9	10	19
Number of complete trips	16	13	29
(Number of incomplete trips)	(1)	(6)	(7)
Maximum trip distance [km]	72.7 ± 37.3	55.0 ± 25.5	64.8 ± 33.2
(Minimum–maximum)	(30.9–138.1)	(27.5–105.0)	(27.5–138.1)
Total trip distance [km]	174.6 ± 120.2	140.3 ± 89.4	159.2 ± 107.1
(Minimum–maximum)	(71.3–527.6)	(66.1–380.5)	(66.1–527.6)
Trip duration [h]	26.0 ± 24.6	18.8 ± 7.0	22.8 ± 18.9
(Minimum–maximum)	(16.8–115.0)	(16.3–42.0)	(16.3–115.0)

ᵃ Sample sizes of individuals, complete (uninterrupted) trips, and incomplete (interrupted) trips are shown. The average, standard deviation, minimum values, and maximum values of complete trips are shown for the maximum trip distance (linear distance from colony to the furthest point), total trip distance (sum of distances between consecutive points), and trip duration (time lapse between departure and return).
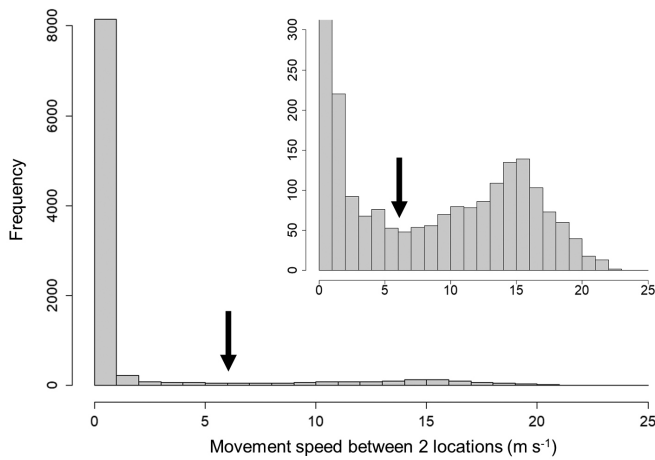
Fig. 2. Histogram of the movement speed (m s^{-1}) of Rhinoceros Auklets *Cerorhinca monocerata* between consecutive locations at sea, recorded at five-minute intervals by GPS loggers. The right upper panel (cutting off the upper y-axis) shows a clear bimodal distribution. Following Zavalaga *et al.* (2010), we categorized bird movements as "sitting" (on the sea surface) or "flying" when the recorded speed was slower or faster, respectively, than the valley of the bimodal distribution (6 m s^{-1}, indicated by arrows).

Altitude accuracy is recorded as a three-dimensional GPS position and varies depending on the logger model, positioning interval, and number of satellites captured at each location (Thaxter *et al.* 2015). Logger estimation accuracy, confirmed by experiment, was highest when more satellites were captured (*cf.* Appendix 2, Fig. S1). In particular, the absolute error was approximately 20 m when the number of satellites was six or more (21.5 ± 27.0 m, five-minute positioning interval); therefore, for the altitude analysis, we used points verified by ≥ 6 satellites. Although loggers often recorded negative altitude values (< 0 m) even when the birds' activity was classified as flying, we did not correct this error because negative values are useful for investigating overall trends such as average values (Péron *et al.* 2020).

We predicted that the auklets would fly at higher altitudes when departing from and returning to their breeding sites and at lower altitudes when travelling at sea. We classified their flights into three phases: a leaving phase, a homing phase, and a foraging phase. The leaving phase took place when the birds left their nesting burrows and took off; we defined this phase as the series of flight points occurring immediately after departure from the island, and the last point in the series was designated as the end of the phase (17 points, 7 series, 1–4 points per series). The homing phase comprised the series of flight points occurring just before arriving at the island, and the first flight point of the series was designated as the beginning of the phase (196 points, 21 series, 1–35 points per series). All other series of flight points were defined as the foraging phase (923 points, 296 series, 1–24 points per series). In this study, the speed at time "*t*" was calculated by dividing the distance moved from "*t*" to "*t* + 1" by the elapsed time (approximately five minutes). Therefore, if the travel distance within five minutes was less than 1800 m, the calculated speed was slower than 6 m·s^{-1} and the bird was classified as sitting. For 11 trips, behavior at a single point located 1262 ± 759 m from the breeding site and recorded just before arrival at the breeding site was classified as sitting based on the calculated speed (Fig. 3A). We believe that these points were classified as sitting because the
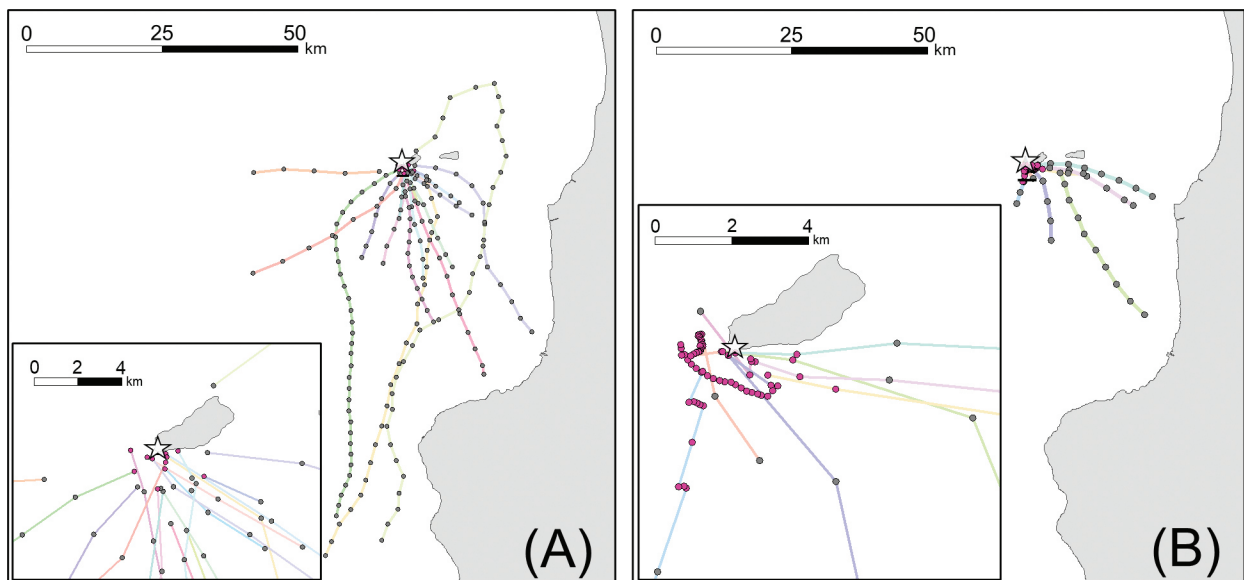
of birds (e.g., Jakubas *et al.* 2016), but speed measurement was not possible in our 2018 data. Although we used the same model GPS loggers (CatLog Gen2) in both 2018 and 2019, the recorded parameters differed slightly between lots. Thus, we used calculated speed in order to retain the same quality of data in both years. In 2019 when measured speed data was available, we found that auklet at-sea activity (flying or sitting with 6 m·s^{-1} as a threshold) based on both calculated speed and measured speed was the same at 92% of the points. Thus, we believe that we could detect flying using the calculated speed.

Fig. 3. (A) Flight point tracks (*n* = 21) for the homing phase of Rhinoceros Auklets *Cerorhinca monocerata* that were used in the analysis. (B) Eight tracks containing flight points and consecutive sitting points immediately before arriving at the breeding site that were excluded from the analyses. Different colored lines show different foraging trips. The color of a point indicates the speed at that point (≥ 6 m·s^{-1}, gray, flying; < 6 m·s^{-1}, pink, sitting). The breeding site, Teuri Island, Japan, is indicated with a star.

position was so close to the breeding site (< ~1800 m); therefore, we have assumed that these points in all 11 trips were classified as flying in the homing phase. However, during eight other trips, we observed consecutive points classified as sitting immediately before arrival at the breeding site, perhaps indicative of rafting on the sea surface (Fig. 3B), and we could not distinguish the series of flights before the sitting period from either the homing phase or foraging phase. Thus, we excluded them from our classification and analysis. We did not analyze the leaving phase further due to the small sample size, because the activity at the points immediately after leaving the island was classified as sitting (< 6 m·s⁻¹) on 29 out of 36 trips. The auklets typically sat on the sea surface near the colony (mean ± standard deviation, min–max: 20 ± 20 min, 5–90 min, n = 29 trips) immediately after leaving the colony but before flying to their foraging area, as described by Kato *et al.* (2003). Because our GPS logger sampling interval was five minutes, it was impractical to extract a brief period of flight behavior. Therefore, we combined the leaving phase with the foraging phase for analysis, rather than analyzing the leaving phase independently.

For the following analysis, points were filtered based on the number of satellites (≥ 6) for positioning. In the combined leaving and foraging phase, we recorded 763 points (258 series), whereas in the homing phase, we recorded 175 points (20 series). To compare the change in flight altitude of the points against the distance from the colony, we created generalized additive mixed-effects models (GAMMs) that incorporated distance from the breeding site as a fixed variable as well as individual identifier as a random variable. The analyses were conducted separately for the homing phase and the combined leaving and foraging phase. The significance of the fixed variable was tested by analysis of variance (ANOVA). All statistical analyses were performed using R 4.0.2 (R Core Team 2020), including the "mgcv" package for the GAMMs (Wood 2004).

RESULTS

Our tracked individual Rhinoceros Auklets remained at sea, presumably foraging, in the southern and southeastern coastal areas in 2018 (Fig. 1A) and in the southeastern coastal area and western offshore area in 2019 (Fig. 1B). The flight altitudes recorded at each point ranged from −224 to 154 m, with the majority of points between −9 m and 10 m (n = 950 points, Fig. 4A). During the combined leaving and foraging phase, the distance from the

breeding site did not affect flight altitude at any point (GAMM: $edf = 1.958$, $F = 1.954$, $p = 0.15$, Fig. 4B). However, the model for the homing phase indicated that flight altitude increased rapidly at distances of 5–10 km away from the colony, reaching 60 m close to Teuri Island (GAMM: $edf = 7.469$, $F = 10.14$, $p < 0.001$, Fig. 4C).

DISCUSSION

During the combined leaving and foraging phase, Rhinoceros Auklets flew at altitudes averaging < 1 m, regardless of the distance from Teuri Island (Fig. 4B). During the homing phase, auklets also flew at low altitudes but ascended to higher altitudes within 5–10 km of the island (Fig. 4C). Previous studies of alcids in areas where offshore wind farms were proposed or constructed have investigated flight altitude by radar or by observation from boats. The probability of Common Murres *Uria aalge*, Razorbills *Alca torda*, Little Auks *Alle alle*, Black Guillemots *Cepphus grylle*, and Atlantic Puffins *Fratercula arctica* flying at altitudes above 20 m at sea has been shown to be less than 1% (Bradbury *et al.* 2014, Johnston *et al.* 2014). By using continuous GPS tracking, we found that Rhinoceros Auklets flew at low altitudes during the foraging phase, supporting previous findings made by snap-shot observation. Although we also observed auklets flying higher temporarily during the foraging phase, we are unable to discuss the probability that they fly higher during this phase because the accuracy of our altitude data was too low for fine spatio-temporal-scale analysis.

We recorded auklets flying at high altitudes in the vicinity of their 120–130 m high breeding site on Teuri Island during their homing phase. Our model clearly indicates that the probability of auklets flying higher increases within 5–10 km from their breeding site. In order to attain the altitude of the nesting colony, a gradual ascent from a distant location may be more efficient energetically than a final steep ascent from a location close to the nesting site. Hedenström & Alerstam (1992, 1994) studied the theoretical climb rate of migrating birds and predicted both a potential maximum climb rate and a slower optimal climb rate; they confirmed that Red Knot *Calidris canutus* climb using the optimal energetic strategy (Hedenström & Alerstam 1994, see also Piersma *et al.* 1997). Tucker & Schmidt-Koenig (1971) had previously measured the air velocity vectors of various flying waterbirds, including ducks, gulls, terns, and herons, and reported that a gentle ascent (2–5°) was observed more often than a steep ascent (> 5°). If
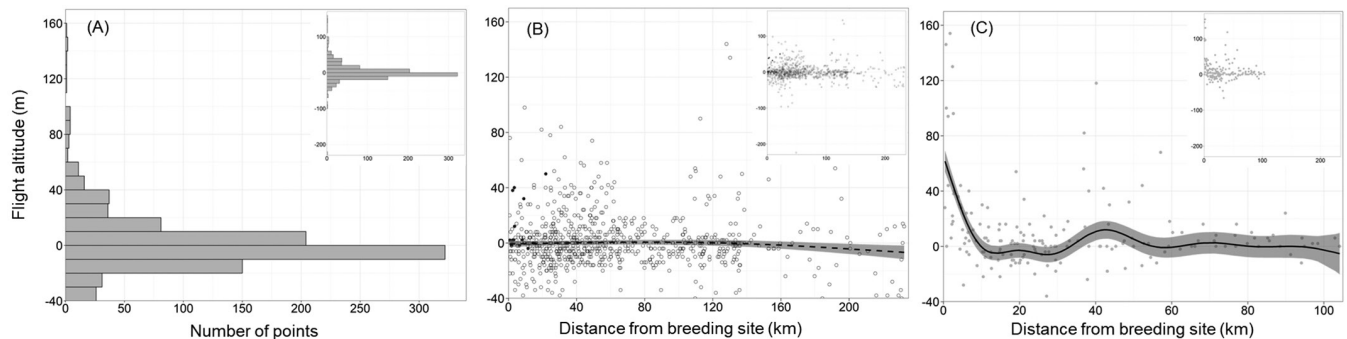

Fig. 4. The flight altitude of Rhinoceros Auklets *Cerorhinca monocerata* at sea, as recorded by GPS loggers accessing at least six satellites. (A) Histogram of flight point altitudes. Scatter plots show the relationship between flight point altitude and distance from the breeding site (B) during the combined leaving and foraging phase and (C) during the homing phase. The small graphs in the upper right corner of each panel show the overall distribution of all values. In each plot, we indicated the predicted value (line) and standard error (shaded area) calculated using generalized additive mixed-effects models. The effect of distance from the breeding site on flight altitude was significant (ANOVA, *p* < 0.05) in the homing phase (solid line) but not the foraging phase (dashed line).

Rhinoceros Auklets ascended at this shallow angle of ascent and at a general flying speed of 15.3 m·s^{-1} (Kikuchi *et al.* 2015), they would require 1.5–4.0 km to attain an altitude of 130 m (calculated by trigonometric function). However, our model predicts that the probability of high flight increased within 5–10 km of the colony, which is somewhat further than the theoretically required distance for the ascent. At sea, the wind becomes stronger at higher altitudes, and high-flying seabirds must adjust their direction to compensate (Tarroux *et al.* 2016, Yonehara *et al.* 2016). Furthermore, seabirds seem to adjust their flight speed more quickly in a tailwind and more slowly in a headwind (Elliott *et al.* 2014). Thus, the distance over which auklets ascend to 120–130 m may vary with flight speed or the ease of ascent, depending on the wind direction and speed.

The flight altitude of Rhinoceros Auklets around their breeding sites is likely to depend on the altitude of their nesting areas. The elevation of nesting areas on Teuri Island varies from 10–180 m (Biodiversity Center of Japan 2017). Moreover, similar variations in breeding-site elevation around Hokkaido (estimated from maps of nesting areas and topography, GSI 2021) were confirmed to be 50–210 m on Matsumae-Kojima (Biodiversity Center of Japan 2017), 20–60 m on Daikoku Island (Okado *et al.* 2019), 10–44 m on Todo Island (Hasebe & Senzaki 2016), 20–30 m on Yururi Island, and 30 m on Moyururi Island (Biodiversity Center of Japan 2018). Our research indicates that Rhinoceros Auklets start ascending, steadily increasing the altitude of their return flight, from several kilometers away from their nesting colony. Therefore, the potential for collision with wind turbine blades may increase within the range of high-elevation breeding sites. In such areas, the risk of Rhinoceros Auklets colliding with not only offshore wind turbines but also inshore ones along coastal cliffs must be considered during wind farm construction planning.

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