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Tracking Wintertime Behaviour of Emperor Penguins Using High-Resolution Synthetic Aperture Radar Imagery

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ABSTRACT

Gaining insight into population changes of species in remote areas of the world poses challenges, often resulting in opportunistic observations (convenience sampling) that limit scientific inference. Remote sensing resources, typically high-resolution optical imagery, have revolutionised population ecology especially in polar regions like Antarctica and now many species have been censused. However, estimates based on remote sensing often remain limited to convenience sampling, rather than allowing observation at times of year that provide more information about the breeding population. Here we introduce a proof of concept using high-resolution synthetic aperture radar (SAR) imagery to detect, enumerate and track behaviours of emperor penguins during the Antarctic winter. Using 25–30 cm Umbra SAR imagery, we gathered images at six colonies of emperor penguins during winter 2024 to determine phenology, to gain insight to the breeding population and advance a new method for breeding population observations. We found that emperor penguins are identifiable on fast ice and that SAR-based observations match concurrent field observations (at Atka Bay). Total huddle area correlated with average colony size at emperor penguin colonies, and we found that larger colonies tended to use more space on the fast ice than smaller colonies. We demonstrate that the breeding population of emperor penguins during winter can be estimated using a combination of SAR imagery with phenological-behavioural models. Given that models suggest emperor penguins may be quasi-extinct before 2100, our work provides an important next step in understanding the approximate size and phenology of the breeding population, information that would be required for conservation of the species and for area-based conservation such as evaluation of the Ross Sea Marine Protected Area (MPA), where ~33% of emperor penguins exist.

1 | Introduction

Our understanding of the distribution of biodiversity around the world is biased towards regions with relatively large financial resources, and so well-surveyed areas tend to be focused in areas of high human density, such as in Western Europe (García-Roselló et al. 2023). For example, marine mammal and seabird species—inherently distant from

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humans—represent only ~2% and ~6% of occurrences within their taxonomic classes, respectively, in the Global Biodiversity Information Facility (García-Roselló et al. 2023). Exacerbated by rapid environmental change, research to inform conservation of wildlife occurring remotely from human populations poses substantial logistical, resourcing and data collection challenges. The difficulty in accessing such populations leads to infrequent surveys, if any, that would lend information about a species' status, such as population counts. Even easily accessible species are often monitored through abundance indices (e.g., Breeding Bird Surveys (Newson et al. 2005)), which are not actual population estimates, and can only be applied to make relative interpopulation comparisons or to monitor trends within a population (Engeman 2005; Anderson 2003; Caughley 1977). With little reliable information on population size and trends, our ability to infer environmental drivers and implement conservation measures remains challenging.

Remote sensing resources have emerged in recent decades as a tool for assessing large-scale changes in land cover (Aguirre-Gutiérrez et al. 2012) and biodiversity (Cohen and Goward 2004; Leimgruber et al. 2005) that may be distant from human centres. The advent of optical, very high-resolution (VHR; 0.3–1.0 m spatial resolution) satellite imagery and its use to identify and enumerate previously inaccessible populations of large-bodied animals (LaRue et al. 2017) has revolutionised aspects of wildlife ecology. Now dozens of species have been detected, and some estimated, using VHR including polar bears (*Ursus maritimus*) (Stapleton et al. 2014), African elephants (*Loxodonta africana*) (Duporge et al. 2021), albatross (*Diomedea exulans*) (Fretwell et al. 2017) and penguins (e.g., Adélie penguins [*Pygoscelis adeliae*] (Lynch and Larue 2014), emperor penguins [*Aptenodytes forsteri*] (LaRue et al. 2024)); several review papers showcase the capacity of VHR imagery (Hollings et al. 2018; Rodofili et al. 2022; Delplanque et al. 2024). Further, with VHR data dating back ~20 years, understanding change over time for some species is now possible (LaRue et al. 2024, Strang et al. 2025). However, despite advances in image and spectral resolution, optical VHR surveys can be hindered by cloud cover and limits to sun elevation for data acquisition (LaRue et al. 2017, 2022). Thus, data collection may be relegated to satellite-defined time frames rather than when it is optimal for learning about the species' life history. This approach is considered convenience sampling (Johnson 2008), and can pose issues with inference derived from such estimates. A further statistical challenge associated with sporadic VHR imagery is that not all animals are available for detection at the time of imaging. Unless the detection function is modelled, abundance estimates can be biased (Buckland et al. 2023). This step is often skipped.

The emperor penguin has a circum-Antarctic distribution (66 known colonies along the coastline (Fretwell 2024; Fretwell and Trathan 2021)) with recent, successful estimation of both a global baseline (Fretwell et al. 2012) and subsequent decadal update (LaRue et al. 2024) using remote sensing. Because their breeding season begins in the austral autumn and continues through the Antarctic winter in complete darkness (Stonehouse 1953), populations of breeding emperor penguins have been previously impossible to study outside of a few colonies near research stations (e.g., Dumont D'Urville Station, near Pointe Géologie). Wintertime estimates of breeding population size would be fundamental for understanding population change. However, due to accessibility issues, all estimates of regional or global populations of emperor penguins at colonies have been conducted during spring (Fretwell et al. 2012). This means current VHR estimates represent, at best, an index of abundance and remain an unknown and variable portion of the breeding population from the previous winter (Winterl et al. 2024). Indices of abundance have limited inferential power (Winterl et al. 2024; Labrousse et al. 2022) and require caution, especially when being used to inform conservation and management action.

Based on research relating adult survival to sea ice extent (Barbraud and Weimerskirch 2001), modelling studies suggest that emperor penguins may go quasi-extinct by 2100 with refugia for the species in the Ross and Weddell seas (Jenouvrier et al. 2025, 2014). With pack ice extent in the Southern Ocean changing rapidly (Hobbs et al. 2024) and with little understanding of how their fast ice habitat may be impacted in the future, gaining insights into environmental covariates related to population trends (at regional and global scales) is a research and conservation priority. The inability to understand the wintertime breeding population of emperor penguins represents a previously insurmountable problem towards insights about species status.

Synthetic aperture radar (SAR) enables collection of the Earth's surface beyond traditional optical sensing capacities (e.g., the aforementioned VHR imagery) (Betbeder et al. 2017; Imhoff et al. 1997; Brown et al. 2010) by operating independently of solar illumination and penetrating cloud cover. Here we wished to observe wintertime colony behaviours of emperor penguin populations in the Ross Sea region and one in the northeastern Weddell Sea by using high-resolution SAR data (i.e., Umbra Space's SAR constellation). Our aims were to: (1) ascertain breeding phenology and colony structure at several colonies; and (2). detect and enumerate breeding populations of emperor penguins. We hypothesised that: (1) colony spatial dynamics will be correlated with colony size, with largest colonies using more surface (sea ice) area than smaller colonies; and (2) northern colonies will arrive at breeding grounds earlier than southern colonies due to their relative proximity to the marginal ice zone in autumn (the edge of the pack ice).

2 | Methods

Our study areas included emperor penguin colonies in both the eastern Weddell Sea (Atka Bay) and the Ross Sea (Figure 1). We chose these colonies because they are relatively well-studied, and in the case of Atka Bay, was the location of an overwinter film crew in 2024, providing an opportunity to compare field observations with concurrent SAR imagery. Atka Bay is home to a colony of ca. 8600 breeding pairs (Richter et al. 2018), which can split into several colony segments, tending to be either on the fast ice or on the ice shelf, depending on the time of year (Fretwell et al. 2014). The bay itself is large and fast ice, on which emperor penguins breed (Stonehouse 1964), persists well into the summer season. In the Ross Sea, emperor penguin colonies are diverse in their habitats (e.g., associated with capes, bays and islands (Fretwell and Trathan 2021)) and the size of

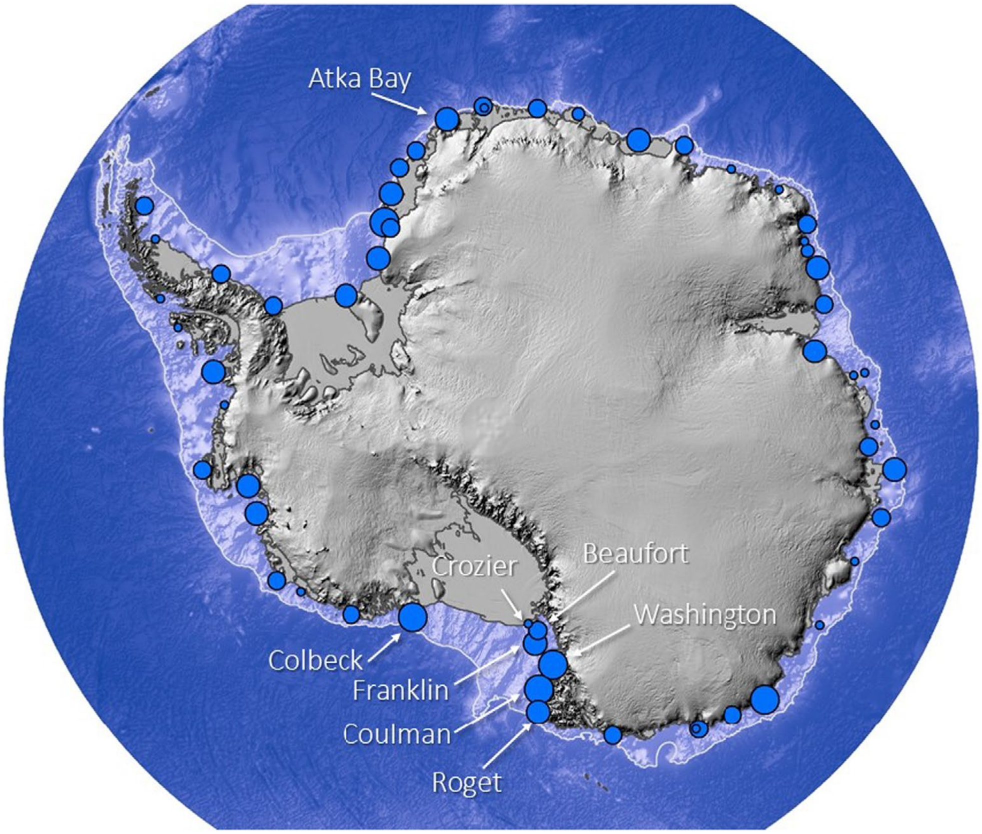

FIGURE 1 | Emperor penguin colonies (scaled to relative colony size) along the Antarctic coastline with colonies in this study (seven in the Ross Sea, one at Atka Bay) labelled in white text, which were tasked for high-resolution SAR imagery acquisition for this project.

colonies ranges from ~500 birds to > 25,000 (LaRue et al. 2024). Both the Weddell and Ross Sea regions are associated with wide continental shelves, relatively stable sea ice conditions and represent most of the primary productivity in the Southern Ocean (Arrigo et al. 2015).

We aimed to determine a wintertime chronology of the emperor penguin breeding cycle using high-resolution SAR imagery provided by Umbra. We further wished to learn about colonies through huddle characteristics from which breeding population size could be estimated. To do this, we tasked images at each colony location (LaRue et al. 2024) using Umbra Space's online Canopy system. We focused our collection parameters on ground resolution, opting for 25–30 cm resolution imagery when possible, and accepting varying grazing angles and polarisations (Betbeder et al. 2017; Osmanoglu and Jo 2023). We hypothesised that changes in colony behaviour would allow for inference of wintertime events inherent to the biology of the species and that these changes would be consistent across all colonies. More specifically, we hypothesised that northern colonies would be detected earlier in the year than southern colonies (Winterl et al. 2024), and larger colonies would be associated with more, but similar-sized huddles (i.e., there would be an asymptotic area for huddling). We suggested that smaller colonies would move through the courtship phase faster than larger colonies (i.e., fewer birds make it easier to find a mate). Finally, we suspected that larger colonies would create larger footprints at their sites, in keeping with the notion that more animals will take up more space (Schwaller et al. 1989).

Upon successful image collection for the Atka Bay colony in April 2024, we downloaded near real-time images to determine our ability to detect huddles and to learn about ice conditions. To do this, we loaded GeoTiff images into ArcGIS Pro (version 3.0) and visually reviewed images, annotating huddle locations, ice edge, icebergs and other features on the landscape that could help with future image interpretation. We then set a consistent image tasking through the winter for Atka Bay, plus all seven Ross Sea colonies (Cape Roget, Coulman Island, Cape Washington, Franklin Island, Beaufort Island, Cape Crozier and Cape Colbeck; Figure 1). After August 2024, we obtained 122 images via Amazon S3 bucket due to large file sizes. We organised images chronologically by colony and then loaded each image into ArcGIS Pro for visual interpretation and manual delineation.

To advance our proof of concept we began our analysis with Atka Bay because it represented the only colony where there were daily camera images being taken (via SPOT (Richter et al. 2018) camera), as well as a film crew observing the colony and opportunistically taking notes. When images were loaded in ArcGIS Pro we created a polygon shapefile to manually delineate huddles and calculated huddle sizes on each image of the colony through the winter (at Atka Bay, $n = 15$ images during winter 2024). We took notes about major events occurring in the colony, including: arrival, copulation, female departure, peak huddle (i.e., males only) and female return/chick hatching. We anticipated that penguins would arrive at Atka Bay in April (Winterl et al. 2024), with all breeders present by the end of May and peak huddling (male incubation) activity occurring in July. Accordingly, we expected the relative population size, as ascertained by the number and area of huddles, to be highest in May and lowest in July (Winterl et al. 2024).

We then calculated huddle areas and number of huddles at Atka Bay through the winter and recorded all pertinent notes per image date. We recorded these data within ArcGIS Pro and extracted the shapefile dataset to a .csv file, resulting in a dataset comprised of records for each huddle, from which we then were able to use the R package "tidyverse" (in R 4.2.2) to summarise our data and calculate metrics per date. We then compared our notes, primarily of phenological events, to those of the ground team to help calibrate our image interpretation. After ensuring our observations corresponded to those of the Atka Bay-based field crew, we created a chronology for Atka Bay and then moved on to repeating the delineation, record-taking and area calculations for all other colonies for which we had imagery in the Ross Sea.

One observer delineated all huddles, which were defined visually as distinct white groups on the fast ice, which appeared black. Images were reviewed by another observer for accuracy. We then calculated at each colony: the number of huddles per date, the total area (m^2) of huddles per date and average huddle area per colony for the 2024 winter. In ArcGIS Pro, we also calculated minimum convex polygons (MCP; defined as the smallest polygon containing all huddles where no angle is > 180°) (Burgman and Fox 2003) for each image date per colony, and then dissolved each daily polygon into one MCP per colony. The colony MCP represented the minimum area on the fast ice that the colony used during April through August 2024.

We created chronologies for each emperor penguin colony and compared changes within each colony (changes in numbers of huddle, huddle areas—both sum and mean per colony—and the MCP) and between colonies to determine if there were general patterns that were consistent across locations. Finally, we calculated approximate colony size (number of breeding pairs) based on a previously published phenological-environmental model that was developed with data from the Atka Bay colony (Winterl et al. 2024). Briefly, this model considers the air temperature, wind speed, solar radiation and humidity as the environmental parameters that influence huddle densities and combines that information with a phenological model that describes fluctuations in the number of birds attending the colony over the season (Winterl et al. 2024). Here, we assumed that the smallest huddle size represents males breeding and that emperor penguin behaviour at Atka Bay is representative of the species.

3 | Results

High-resolution SAR imagery can be used to detect the presence of emperor penguin colonies in the Ross and Weddell seas, to determine total number and areas of penguin huddles and to observe phenological change during winter. Appearing visually on SAR imagery as bright white spots on the sea ice (Figure 2), we identified important events including the onset of the mating season, female departure and return from their first winter feeding trip at sea and the winter male huddle at Atka Bay (Figure 3). We observed loose aggregations of birds at Atka Bay in mid-April, and found that first copulation attempts corresponded with observations of 'tight huddles' on the SAR imagery (Figure 3). SAR-based image interpretation suggested that females left only 4 days after the field team observed the beginning of their departure to the sea. The film crew recorded total silence in Atka Bay on June 28 (Day 180), indicating all female penguins had departed leaving only the males. The July 12 image independently suggested the image captured the onset

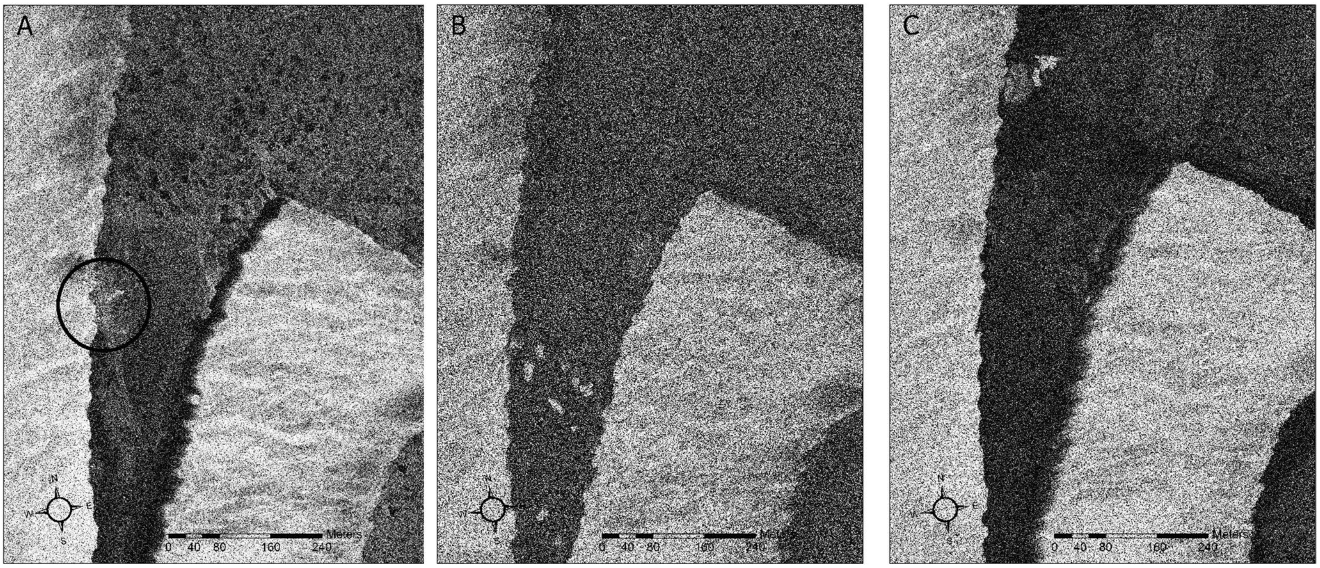

FIGURE 2 | ~25 cm SAR imagery (acquired by Umbra Space) of the Atka Bay emperor penguin colony during winter 2024 showing changes of emperor penguin huddles. The penguin huddles are the smaller, bright white features on the fast ice (which is black) in between the shelter provided by the Ekström Ice Shelf (which is the white ice on the image). Each panel corresponds to a date listed in timeline in Figure 3. (A) Loose aggregations of birds on 12 April 2024 (indicated within the circle); (B) Well-formed groups of birds on 9 May 2024 (many dense groups); (C) Male incubation on 12 July 2024 (few dense groups).

of the male incubation period. Females began to return from their foraging trip approximately 2 weeks before we detected the change on SAR imagery (Figure 3), and chicks were first observed in the field during that time, at the beginning of August.

We received imagery for all Ross Sea colonies but due to minor offsets in possible colony location, we did not successfully capture emperor penguins at Beaufort Island or Cape Colbeck. In general, we observed that the total area of huddles averaged over the winter corresponded with approximate colony size (i.e., Coulman Island had the largest average total area of huddles and Cape Crozier had the smallest huddle area; Table 1, Figure 4). Huddle areas differed among colonies. We also found that the number of huddles varied within colonies (e.g., 2–25 huddles at Coulman Island; 2–5 huddles at Cape Crozier) over the season (Figure 5). However, we consistently observed a peak number of huddles in May–June at all colonies, which we interpreted to be the full breeding population, reducing to approximately half that number in July (the male-only population). We inferred that the smallest number of huddles recorded represented incubating males, from which the corresponding total huddle area could be used to estimate the breeding population. Interestingly, despite Cape Crozier being 800 km south latitudinally of Atka Bay, SAR images indicated that the breeding phenology of emperor penguin colonies was similar in 2024 (Table 2).

We provide preliminary breeding estimates derived from high-resolution SAR imagery at the six colonies included in this study. As expected, we found Coulman Island had the highest estimate for breeding pairs (14 886 breeding pairs) and Cape Crozier had the fewest birds (2147 breeding pairs; Table 2) in winter 2024. Each colony exhibited the same pattern of a peak number of individuals attending the colony during May, followed by the minimum number (males huddling) in July (Figure 5). We did not observe many smaller huddles being associated with larger colonies. Instead, breeding males at Coulman Island—one of the largest colonies in the world—were apparently comprised of one large huddle (2183 m^2; Table 2), whereas its nearest neighbour colony, Cape Washington, comprised eight huddles in the middle of July (Figure 5). The total space used per date at each colony (as calculated by MCP) was correlated with total area of huddles per date ($r^2 = 0.65$), and Atka Bay occupied a larger area of fast ice compared to similar-sized colonies in the Ross Sea (Figure 6). In other words, Atka Bay was more spread out than Ross Sea colonies.

4 | Discussion

Using high-resolution SAR imagery, we provide a proof of concept to detect, enumerate and monitor behaviour at emperor

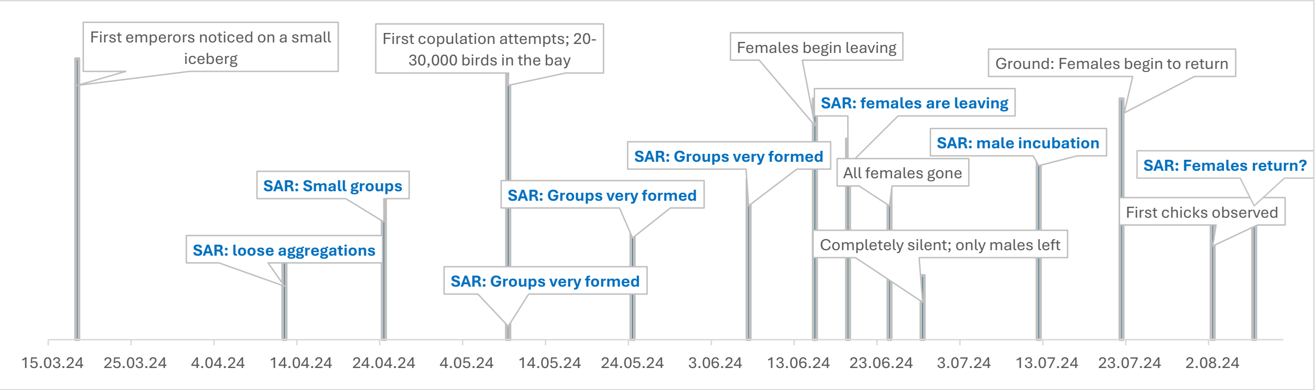

FIGURE 3 | Chronology of observations at Atka Bay emperor penguin colony during 15 March 2024 through 07 August 2024. Timeline is based on direct, field-based observations, and from independent review of SAR imagery (all SAR-only observations on the timeline are shown in bold, blue text). When groups are very well-formed, we can infer that copulation is occurring and notably, female departure occurred before the observation from SAR by only ~10 days.

TABLE 1 | Emperor penguin colonies, the minimum total area of huddles (rounded to the nearest m^2) and the date on which the minimum huddle area was recorded (both calendar and Julian date) assuming that date represents the male-only huddles, and the estimated number of breeding pairs based on recent models (Winterl et al. 2024).

Colony	Minimum area of huddle recorded (m^2)	Date of minimum area of huddle	Julian day of minimum huddle	Approximate number of breeding pairs
Atka Bay	1060	July 12	194	7947
Cape Crozier	275	July 16	198	2147
Cape Roget	722	July 16	198	5113
Cape Washington	1636	July 10	192	9464
Coulman Island	2183	July 16	198	14 886
Franklin Island	878	August 9	222	4778

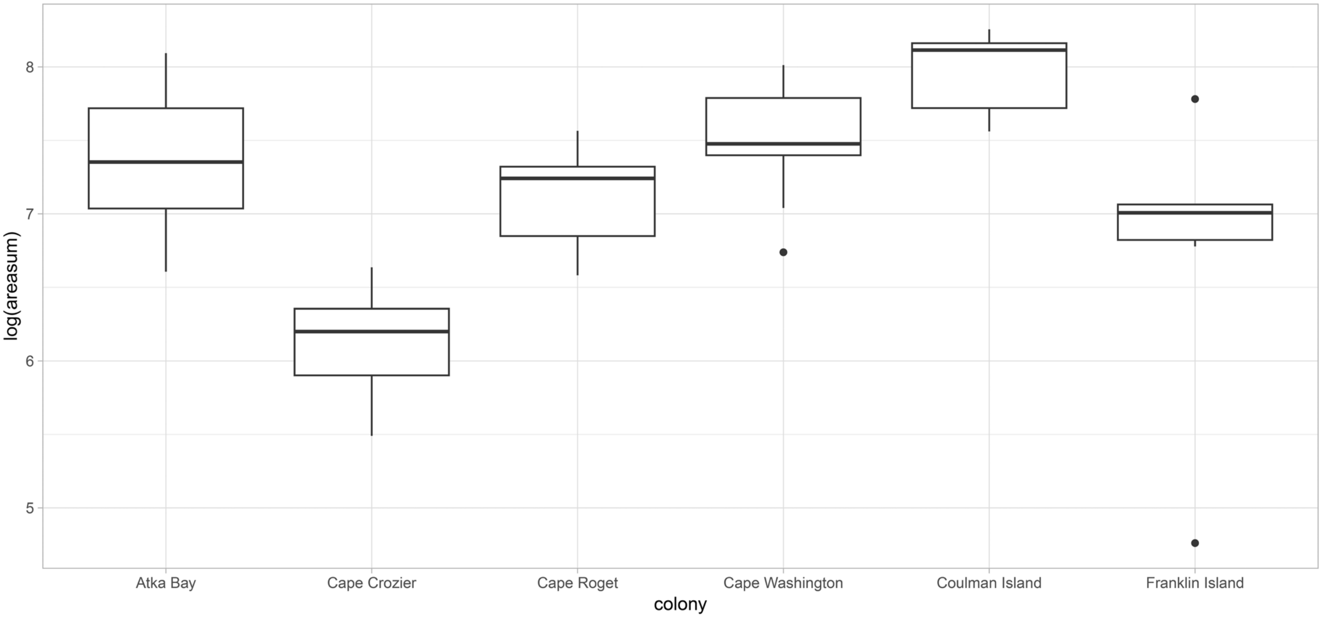

FIGURE 4 | Distribution of total huddle areas per date (y-axis, measured in log m^2) for emperor penguins at each of six colonies (x-axis) for which we had high-resolution, synthetic aperture radar (SAR) Umbra imagery during winter 2024 (April–August).

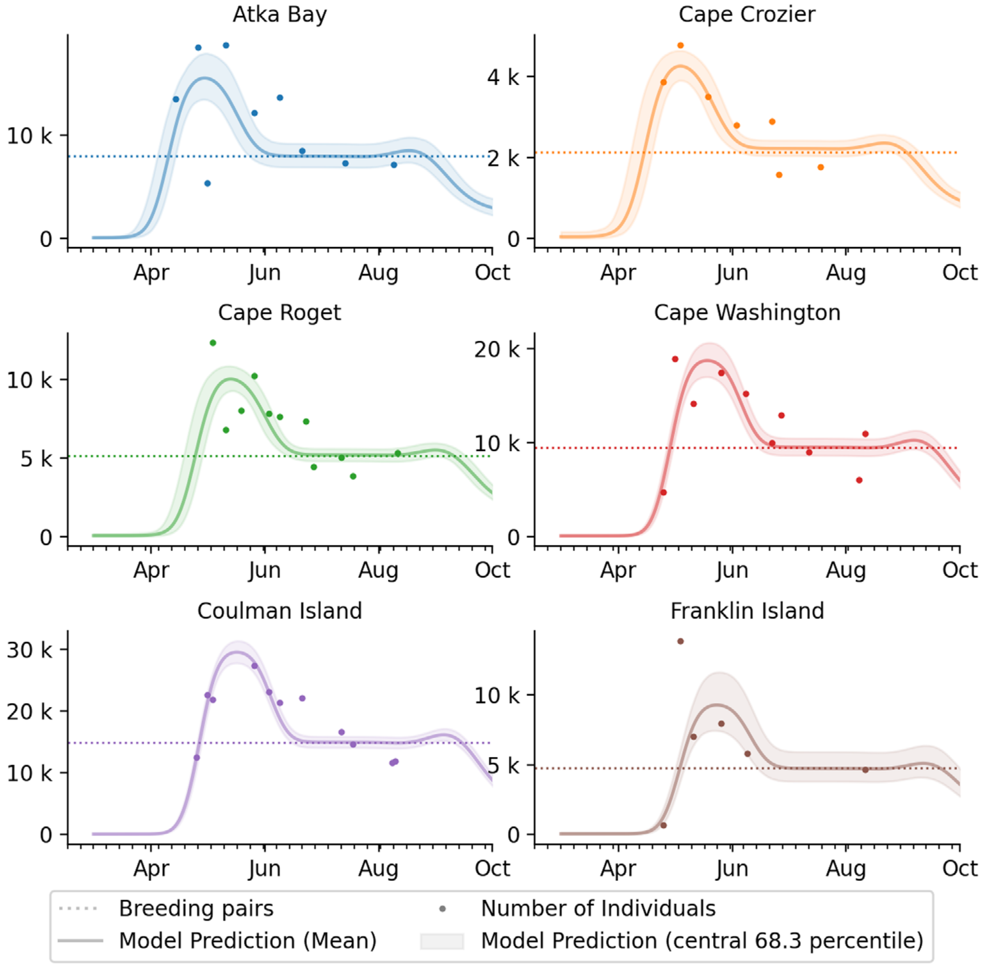

FIGURE 5 | Preliminary breeding population estimates and phenology of emperor penguins at six colonies during winter 2024. Estimates are based on huddle areas per date during winter time, calculated on high-resolution SAR imagery, integrated into the phenological-environmental model designed recently (Winterl et al. 2024).

TABLE 2 | Amount of time elapsed, in days, between observed first copulation signals (small, tight groups) to observed signals of male-only huddling (fewest number of huddles in July), by colony latitude.

Latitude	Colony	Copulation suspected (Julian day)	Male incubation (Julian day)	Days elapsed C-I (approximate)
−70.6142	Atka Bay	130	194	64
−71.9882	Cape Roget	130	198	68
−73.3483	Coulman Island	145	198	53
−74.6373	Cape Washington	130	192	62
−76.1873	Franklin Island	na	na	na
−77.4653	Cape Crozier	138	198	60

Note: Values are in day of year where 1 January is Day 1, and observations are the first time we observed the behaviour on SAR imagery. Therefore observations should be interpreted with caution, as behaviours could have been occurring prior to our having imagery of the colony. Franklin Island is listed but the date of male incubation (i.e., an image in June) was not acquired, precluding calculation of days elapsed.

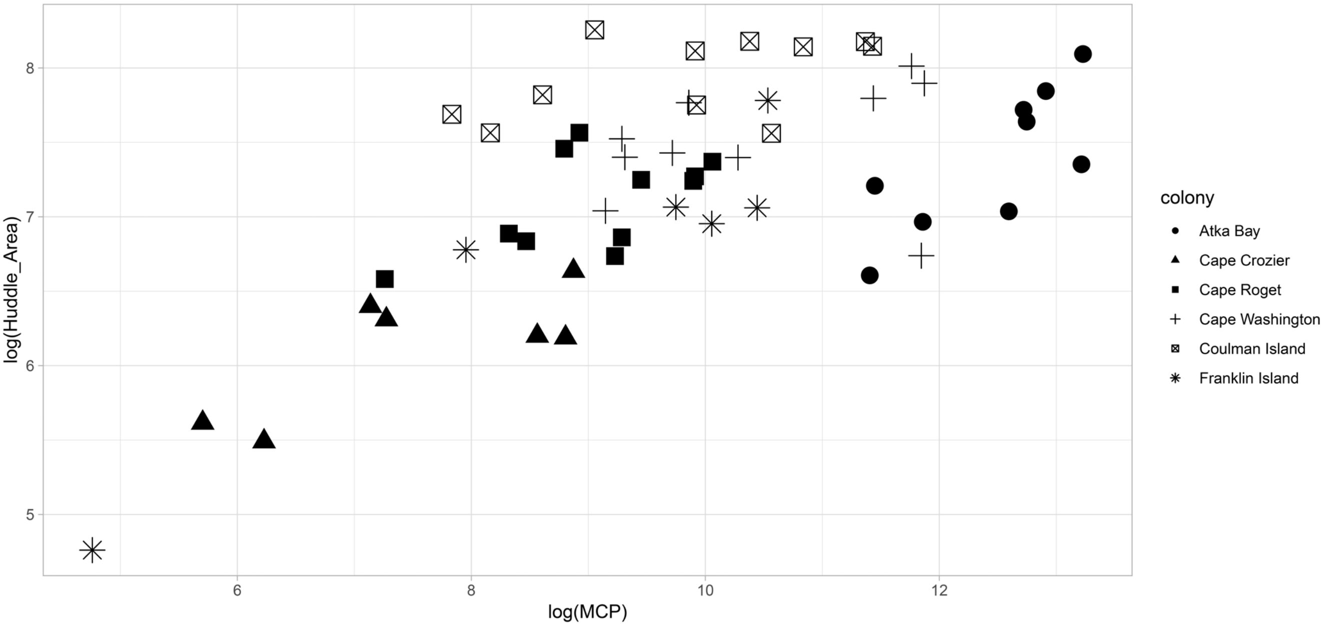

FIGURE 6 | Total area of huddles per day at each colony (y-axis) versus the total area taken up (MCP) across each colony location (x-axis). We found a correlation between huddle area and MCP ($r^2 = 0.65$), though Atka Bay consistently used more space at their colony location given the total area.

penguin colonies during the winter breeding season—a time of year previously inaccessible for remote observation outside of the few colonies located near winter research stations (Winterl et al. 2024; Kirkwood and Robertson 1997; Barbraud et al. 2011). Across several locations in Antarctica and over a latitudinal gradient, we describe phenological events over five months in 2024 and provide estimates of the breeding population of emperor penguins in July (i.e., male-only huddles (Le Maho 1977)); importantly noting ground validation of these estimates will be required. Our estimates here can only be considered preliminary and require further refinement. We show easily detectable changes in huddle structure and size correspond to their life cycle: mating period (with largest total area of huddles and highest number of huddles), females' departure for their first winter foraging trip, the winter male incubation period (identified by the smallest total area of huddles), followed by the female's return. Further, we gained insight into space use at each colony and how huddles are oriented through winter. We suggest high-resolution SAR imagery may serve as an effective monitoring tool, providing valuable context especially when combined with springtime observations using optical VHR imagery (LaRue et al. 2024).

Huddle sizes derived from SAR imagery combined with a phenological-environmental model (Winterl et al. 2024) provided a first estimate of the breeding population of emperor during winter. Our observations comport with known phenology (peak attendance in May, male-only huddles in July) for the species and our preliminary breeding population estimates reflect expectations at the six colonies we studied—primarily that Coulman Island was the largest with Cape Crozier being the smallest (Table 2). We note our results are still not an estimate of the total adult population; that is, all birds of breeding age, as some birds may opt to skip breed (Jenouvrier et al. 2005).

However, in terms of monitoring a long-lived seabird, annual estimates of breeding pairs represent a useful index of abundance because population growth of long-lived species tends to be most affected by adult survival (one vital rate that influences inter-annual fluctuations in numbers of breeding pairs (Sæther and Bakke 2000)) and least affected by vital rates such as chick survival (Hilde et al. 2020). Simply put, breeding bird surveys, conducted consistently over long periods, represent a global standard for gaining insights into population change in birds (Newson et al. 2005; Underhill and Prys-Jones 1994; Igl and Johnson 1997). With further ground validation of chick counts and other ground-based winter observations to improve models, we show this is now possible for emperor penguins.

Manual SAR-based image interpretation corresponded with concurrent ground observations (Figure 3), lending confidence in the ability to learn about the phenology of emperor penguins where ground validation is not possible (i.e., most emperor penguin colonies) (Fretwell and Trathan 2021; Trathan et al. 2020). At the six colonies for which we had imagery in winter 2024, it appeared emperor penguins generally synced their phenology irrespective of colony location (at least within a few weeks) and we learned behavioural signals to observe. First, as colonies assembled, the groupings appeared loosely aggregated and this behaviour represents the beginning of mate selection (Le Maho 1977). We then saw a marked change: penguins began huddling together in distinct groups, which at Atka Bay coincided with the onset of the copulation in the middle of May (Figure 3). The first bout of tight groupings also coincided with the maximum huddle areas and presumably the highest number of animals in attendance to that point (i.e., all breeding animals) (Le Maho 1977). For about a month huddles remained well-formed. At the beginning of June groups dispersed, representing the first departure of females for their winter foraging trip (Figure 3), having turned their eggs over to males for incubation (Ancel et al. 2013). After this, the huddles become fewest and densely packed, representing males incubating eggs until the females' return, which occurred at Atka Bay in early August 2024. We observed the break-up of groups via SAR imagery shortly thereafter (Stonehouse 1953). The temporal consistency of these patterns across colonies lends credibility to the utility of SAR for emperor penguin phenology and population estimation.

Detectability of huddles does not appear to be hindered by colony size (e.g., Coulman Island [~25,000 birds] and Cape Crozier [~2000 birds (LaRue et al. 2024)] are at least an order of magnitude different and both were easy to detect). We note, however, that many emperor penguin colonies around Antarctica are much smaller (< 500 birds); we do not know if colonies smaller than Cape Crozier are detectable. We found that the number of huddles corresponded to average colony size, as did mean huddle area (LaRue et al. 2024). However, the total space used by penguins at the colony, as calculated by the MCP per date, was larger at Atka Bay (Figure 6). Given the size of the colony (approximately the same as Franklin Island; Table 2), Atka Bay birds simply used more space because it was available to them. In contrast, Franklin Island is characterised by a plate of fast ice that surrounds the island, with the birds sheltering behind a cape—but there is very little space for them to spread out, and even in years when the ice is more extensive (such as during B-15 years (Arrigo et al. 2002)), they remain close together. If Atka Bay is an indication, given the opportunity emperor penguins may use more space at a colony location if it is available to them during the breeding season.

We suspected that northern colonies would arrive at breeding grounds earlier than southern colonies (Winterl et al. 2024) due to their relative proximity to the marginal ice zone (northernmost edge of pack ice) in autumn but these were not our observations. Rather, the largest differences in phenology across colonies were observed for two colonies at the same latitude. Both Cape Roget (in the Ross Sea) and Atka Bay (in the Weddell Sea) are distant but at approximately the same latitude (~ −70°), and Cape Roget was first detected several weeks later than Atka Bay. Though we acknowledge we cannot easily ascertain exact arrival dates, we suggest this could be due to emperor penguins spending their post-moult in the eastern Ross Sea (Kooyman et al. 2000), which is a > 1000 km journey back to Cape Roget. Depending on the latitude, and therefore day length the birds experienced prior to their return to the colony, their return journey may have happened concurrently for all Ross Sea colonies; but because Cape Roget is most distant from moulting grounds, it may have simply taken longer for birds to return and to be detected on the SAR imagery. Alternatively, their date of first detection may have also been because their fast ice habitat is rougher ('pancake'-looking) and it was more challenging to detect differences in ice surface that could be attributed to the arrival of the birds. Qualitatively, we found colonies that were on smooth, first-year fast ice were quite easy to detect and observe.

A caveat of recent estimates of emperor penguin abundance derived by remote sensing, is that surveys based on optical sensors are limited to springtime (LaRue et al. 2024; Fretwell et al. 2012; Labrousse et al. 2022) (convenience sampling (Anderson 2003)) and therefore represent an unknown and variable subset (both spatially and temporally) of the breeding population from the previous winter. In fact, what springtime indices of abundance represent is still unknown (LaRue et al. 2024), but may be related to fledgling abundance (Şen et al. 2025) because the number of adults at the colony during early spring may represent birds that are still provisioning their chicks (Winterl et al. 2024). Initially, the first global estimate of emperor penguins assumed that the number of birds derived from 'area of penguins' on optical images during spring represented half the breeding population and could therefore be doubled, resulting in a global estimate of ~238,000 breeding pairs (Fretwell et al. 2012). However, recently this assumption was updated (LaRue et al. 2024) as the substantial year-on-year variability in adult and chick counts (the latter of which can be considered a conservative estimate of number of breeding pairs (Schmidt and Ballard 2020)) suggests that springtime counts of adults are an unreliable index of breeding pairs (Kooyman and Ponganis 2017; Barber-Meyer et al. 2008). For example, based on counts from aerial surveys at Beaufort Island in spring 2004, adult penguins outnumbered chicks counted by nearly 7:1, whereas at Franklin Island in 2006, the chick count was nearly double the count of adults at the same time of the year (Kooyman and Ponganis 2017). At Cape Colbeck in spring 2010, the ratio of adults to chicks ranged from 2.6:1 down to nearly 1:1 the following year (Kooyman and Ponganis 2017). Consequently, while abundance estimates from remote sensing (as springtime indices of abundance) of emperor penguins exist for 50 colonies over 10 years (LaRue et al. 2024), the Weddell-Bellingshausen sector ($n = 16$ colonies) for 15 years (Fretwell et al. 2025) and the Ross Sea for 20 years (Foster-Dyer 2025, Foster-Dyer et al. 2026), we cannot relate adult-to-chick counts to reliably obtain estimates of breeding pairs using springtime indices; nor can we suggest that adult counts during spring alone can consistently index the number of breeding pairs. It therefore remains that a reliable global estimate of breeding population size does not yet exist, and the only consistent winter estimates are from Atka Bay (Winterl et al. 2024; Richter et al. 2018) or Pointe Géologie, the longest-studied colony of emperor penguins on the planet (Barbraud and Weimerskirch 2001; Le Scornec et al. 2025). With observations from SAR combined with the phenological-environmental model (Winterl et al. 2024), a first ever breeding estimate for emperor penguins may now be possible.

The addition of high-resolution SAR imagery in the research toolbox serves as an important advancement in our ability to monitor emperor penguin populations and behaviours during a time in their life cycle that has been elusive for observation (LaRue et al. 2022; Larue and Knight 2014). Connecting wintertime SAR observations and indices of the breeding population with optical VHR-derived springtime indices of abundance (LaRue et al. 2024; Fretwell et al. 2012, 2025; Winterl et al. 2024) will pave the way for a full view of the emperor penguin life cycle around Antarctica (Fretwell 2024; Fretwell and Trathan 2021). However, we note that these new methods require validation from other field-based methods such as aerial or ground counts of adults and chicks and complemented by demographic studies. Given conservation urgency associated with the species (Jenouvrier et al. 2025, 2021; Trathan et al. 2020), gaining precision in our understanding of population fluctuations and environmental covariates associated with changes remains paramount.

Author Contributions

Michelle LaRue: conceptualization, investigation, funding acquisition, writing – original draft, methodology, validation, visualization, writing – review and editing, formal analysis, project administration, data curation, supervision, resources. **Daniel Price:** investigation, methodology, validation, writing – review and editing. **Sarah Wiki-Bennett:** conceptualization, investigation, funding acquisition, writing – original draft, writing – review and editing, supervision, resources. **Charles K. Lee:** conceptualization, investigation, funding acquisition, writing – original draft, writing – review and editing, methodology, resources, project administration. **B. Jack Pan:** conceptualization, investigation, funding acquisition, writing – original draft, writing – review and editing, methodology, resources, project administration. **Kyle McCloud:** data curation, resources, writing – review and editing, investigation. **Heather Cruickshank:** investigation, writing – original draft, data curation, resources, validation. **Alex Ponniah:** writing – review and editing, resources, data curation, validation, investigation. **Daniel Zitterbart:** writing – review and editing, visualization, validation, methodology, formal analysis, resources, supervision. **Alexander Winterl:** methodology, validation, visualization, writing – review and editing, formal analysis, resources. **Céline Le Bohec:** writing – review and editing, visualization, validation, methodology, formal analysis, resources, supervision. **Rose Foster-Dyer:** validation, methodology, data curation, writing – review and editing. **Peter Fretwell:** conceptualization, investigation, writing – review and editing.

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Disclosure

Intellectual Contributions: We provided opportunities for the researchers from the country where the study was conducted and included their contributions as co-authors.

Data Availability Statement

We report our results as open data and provide our .csv files and scripts for completing analysis: https://github.com/mla150/SAR-Emperor.

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