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Discovery of Antarctic moulting sites in satellite imagery reveals new threat to emperor penguins

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Moult is a critical period in the life cycle of emperor penguin. Like other stages of their life history they depend upon Antarctic sea-ice as a platform to moult. Our knowledge of where the birds moult is limited to a small number of tracking studies and incidental observations, showing most adult emperor penguins moult in small groups on sea ice between January and March. Sea ice extent and duration has reduced dramatically over the last decade, and understanding how these declining ice conditions are impacting emperor penguins is crucial to model future population trajectories. We show that groups of moulting emperor penguins can be seen in medium and very-high-resolution satellite imagery. The study concentrates on a specific the area of West Antarctica, identifying the distribution and number of moulting groups over a seven-year period (2019-2025). Between 2022 to 2024, reduced fast ice extent resulted in a concentrated distribution of moulting groups and early break-up of the moulting platform before the end of the season.

Emperor penguins (*Aptenodytes forsteri*) are likely to be more at risk from climate change than any other air-breathing Antarctic animal[1]. Their coastal distribution and reliance on sea ice for almost all stages of the life history make them highly susceptible to warming environmental conditions. Research on the impact of climate change on their populations[2–4], and predicted future population changes[5–9], focused exclusively on their breeding colonies, where they spend up to 9 months of each year. Ground studies and satellite surveys over many years have greatly increased our knowledge of these animals at these sites[10–12], but other stages of their annual lifecycle, such as the annual moult, have been less well studied.

Like all penguins, emperor penguins undergo an annual catastrophic moult, where they replace all their feathers over a short period of time[13,14]. This happens after the birds leave their breeding colonies in December and is usually completed before the end of February, giving the birds enough time to regain body condition before returning to the colony locations in late March or early April. All individuals more than one year old must undergo this process. The moult takes 30–40 days[15,16]. Emperor penguins are one of only two species of penguins, along with Adélie penguins (*Pygoscelis adeliae*), that usually moult on sea ice. But exactly where the birds go to moult is poorly known, as only a limited number of tracking studies are published[17–20]. Anecdotal reports and tracking studies show that the preferred moulting habitat is stable fast ice or dense pack ice, and occasionally coastal islands. Ship-based sightings suggest that emperor penguins moult in small groups (several 10s of birds), and occasionally in larger congregations[18]. This period of moult coincides with the annual Antarctic summer sea-ice minimum, between January to early March.

Over the last decade, the extent of Antarctic summer sea ice has reduced significantly, falling from an average (for the satellite period) of 2.8 million km^2 to a record low in 2023 of 1.79 million km^2. This minimum appears to be part of an ongoing trend; the lowest sea ice extent was recorded in four consecutive years from 2022–2025[21,22]. These reductions have not been equal around the continent; some regions, like the Weddell Sea, remained relatively stable, whilst others, such as the Amundsen Sea, lost almost all of their summer sea ice. The consequences of the dramatic regional reduction in sea ice cover are poorly known for penguins and seals that use the ice as a moulting platform and foraging zone over the summer.

For emperor penguins, the moult period is characterised by a high metabolic rate and a long fasting period when the birds cannot go to sea to forage[18]. Even in years with normal sea ice coverage, the moult period is considered high risk to the birds due to the variability of sea ice, especially in summer (February) when sea ice extent is at its minimum. It is probably the period of highest adult mortality, as immersion into the sea before moulting is completed will lead to increased energy usage, possibly hypothermia[18], and increased risk from predators[23] as agility in the water will be compromised. If the animal survives, it may suffer from poor body condition, which will increase the time required to replenish body reserves before breeding. Any delay may lead to deferred breeding, or decreased breeding success for females and an increased chance of winter mortality for males (males have

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higher rates of mortality and shorter lifespans than females due to fasting throughout the incubation period during the Antarctic winter[24]).

The Ross Sea is an important breeding location for emperor penguins. The seven breeding colonies here contain ~30–40% of the global population[12], which is genetically distinct from other populations[25,26]. It is also considered one of the refugia where emperor penguins may survive in the face of future climate change[27]. The Ross Sea is one of the few places where tagging studies documented the movement of adult birds after the breeding season[18,28]. After leaving the breeding colonies, most birds in the Ross Sea head east and moult on the extensive pack/fast ice zone off the western Marie Byrd Land near the Saunders Coast. Trips from breeding colony to moult site are extensive and can cover a distance of 1000 km each way. Birds generally arrive in this location sometime in January and stay until moult is completed in late February or early March. However, since 2016, sea ice extent in the region of Marie Byrd Land has diminished markedly.

The area between Siple Island and Cape Colbeck in Marie Byrd Land has traditionally been an area of extensive stable sea ice (Fig. 1). Over the last 50 years for which we have archival satellite data, at the time of minimal sea ice cover in summer, which coincides with the emperors' moult period in February, sea ice cover in this area has averaged around ~500,000 km^2 (Fig. 1). In most years this ice has been a mix of fast ice near the coast and more broken pack further to the north. The extent of ice in the region has declined significantly in the last five years. In Marie Byrd Land in February 2023, only ~100,000 km^2 of sea ice remained, almost all of which was dynamic broken pack ice several hundred kilometres offshore. Fast ice near the coast was limited to ~2000 km^2 near the terminus of the Land Glacier. As this is thought to be the moult area for Ross Sea emperors, rapid decreases in ice habitat could have implications for emperor penguins and other marine predators that use the ice as a moulting or breeding platform. But the difficulties in studying these animals in this remote and dynamic environment have previously restricted any insights into the impact of these environmental changes.

Here, we test the ability of satellite imagery to detect emperor penguin moulting groups. Using synchronous images taken on the same day, we compare the very high resolution (VHR) satellite imagery to verify the ability of medium resolution Sentinel-2 data to accurately identify moulting groups. We then expand the study in space and time using Sentinel-2 imagery to identify moulting groups over a larger region consisting of the majority of the Saunders Coast over the archival period of Sentinel-2.

Methods

Area of the study

This study was instigated by the chance discovery of what were assumed to be large numbers of emperor penguin moulting groups whilst viewing February Sentinel-2 imagery of the Guest Peninsula (Fig. 2). Searches of archival satellite images of the coastline confirmed that these groups were concentrated on fast ice exclusively in this region. The indicative signal of penguins were small brown patches on the sea ice, these patches were concentrated over a small length of coastline in part of the ocean off to the Saunders Coast in Western Marie Byrd Land, between Groves Island (143° W) and Vollmer Island (151° W), a distance of around 200 km (Fig. 3). It is within an un-named patch of ocean between the Amundsen Sea to the east and the Ross Sea to the west. Over the satellite period, it has been characterised by extensive fast ice cover (the fast ice cover in late January 2020 over the area was ~14,000 km^2). This ice is typically multi-year and is difficult for icebreakers to penetrate; therefore, few ships have been close to the coast here[29]. Other areas of Marie Byrd Land to the west, along the coast to Cape Colbeck at the edge of the Ross Sea (158.5° W), and eastward to Land Bay (141° W) were also searched for the indicative brown pixels, but little or no sign of moulting penguins was found in these areas.

Satellite imagery

Two types of satellite imagery were used in the study. Sentinel-2 data from the Copernicus Programme is a multispectral sensor that continually acquires freely available imagery. This was viewed with a band combination of 8/4/3 (NIR/RED/GREEN), which differentiates the brown patches better than the visible bands[30]. Using these bands, the spatial resolution of the data is 10 m per pixel ground sample distance. Data were searched using the Copernicus Browser (https://browser.dataspace.copernicus.eu/) and analysed after downloading the imagery from this platform. Cloud-free data from 2019 to 2025 were analysed from mid-January to the end of February each year, with a preference for imagery from early February when multiple images were available (Supplemental Table 1 for the list of images). At this time, only emperor penguins moult on the ice; Adélie penguins also moult on sea ice, but not until March[31]. Thus, any penguins seen on the ice at this time were likely to be emperors.

To check that the indicative brown patches were indeed groups of emperor penguins, and to assess how reliably the groups of penguins could be found (i.e., whether we could identify the smaller groups and whether we were misclassifying guano for moulting groups), three sections of VHR

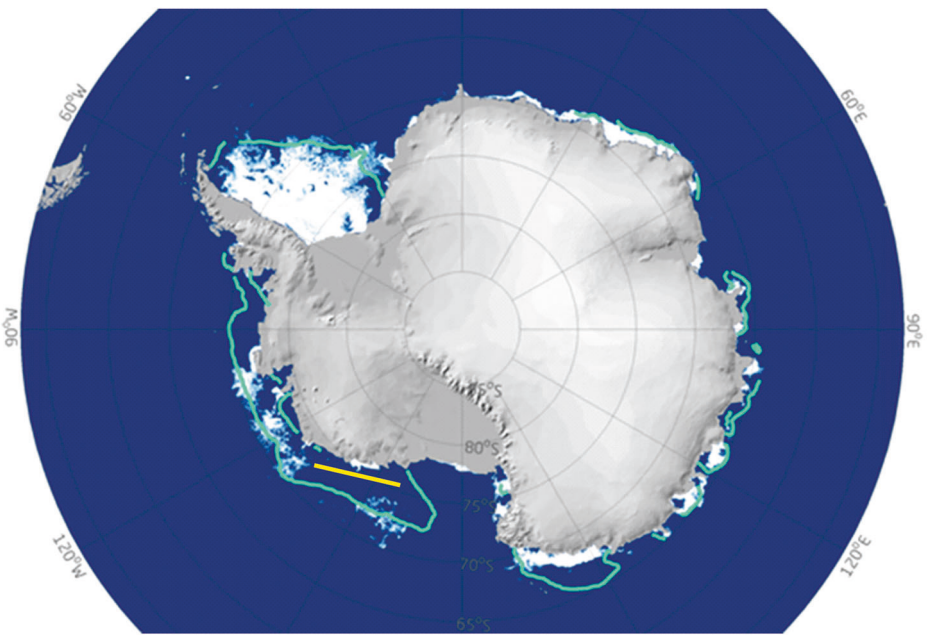

Fig. 1 | Area of sea ice on 21/02/2023 (in white). This was the record low summer sea ice extent in February 2023. The light blue line shows the mean sea ice extent in the satellite period (1978–2025). The yellow line indicates the Marie Byrd Land coast between Cape Colbeck and Siple Island, where tagging studies show Ross Sea emperor penguins moult. Note that the summer sea ice in West Antarctica, especially fast ice near the coast, was virtually all gone in 2023. Data from https://nsidc.org/data/g02135/versions/3.

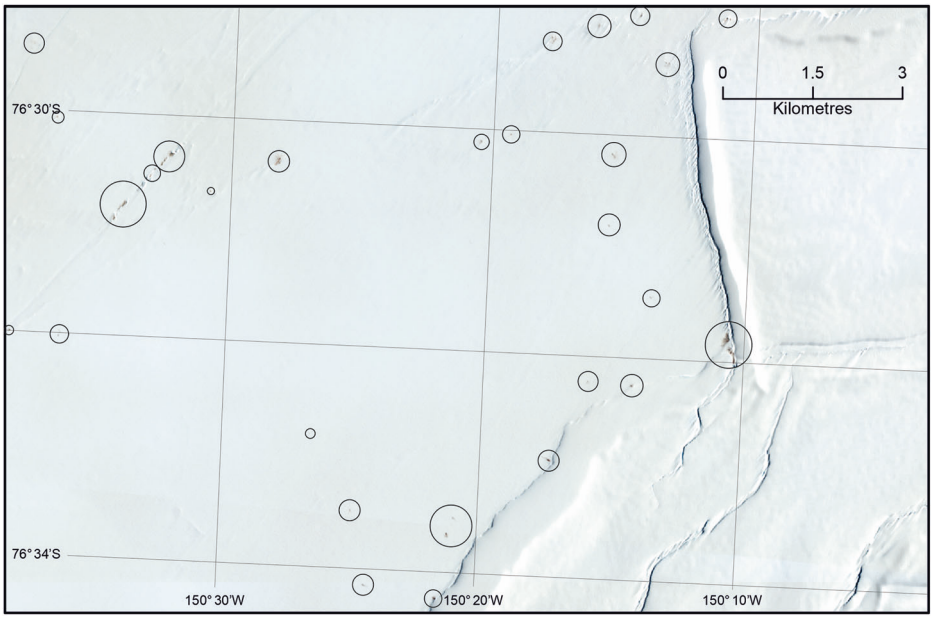

Fig. 2 | Brown patches were seen on the Copernicus browser that instigated this study. Each circled brown patch denotes a possible moulting group or guano patch. Image Sentinel-2 2/04/2022 (Copernicus/ESA2025).

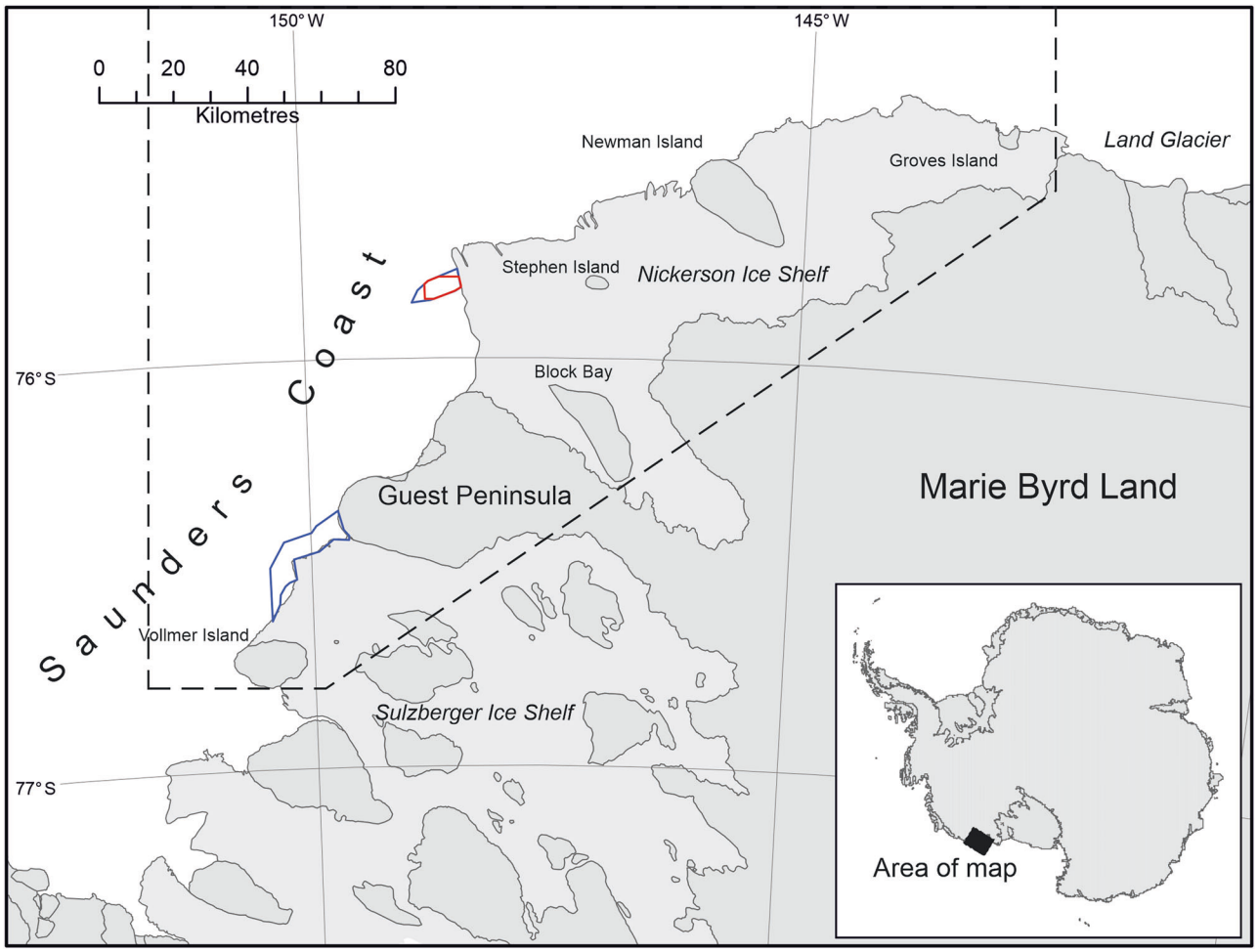

Fig. 3 | Area of study. The dashed area highlights the main area of study where Sentinel-2 data were acquired over the 7-year period. The small blue boxes denote the areas covered by VHR satellite imagery, and the smaller red polygon is the area of synchronous VHR and Sentinel-2 data.

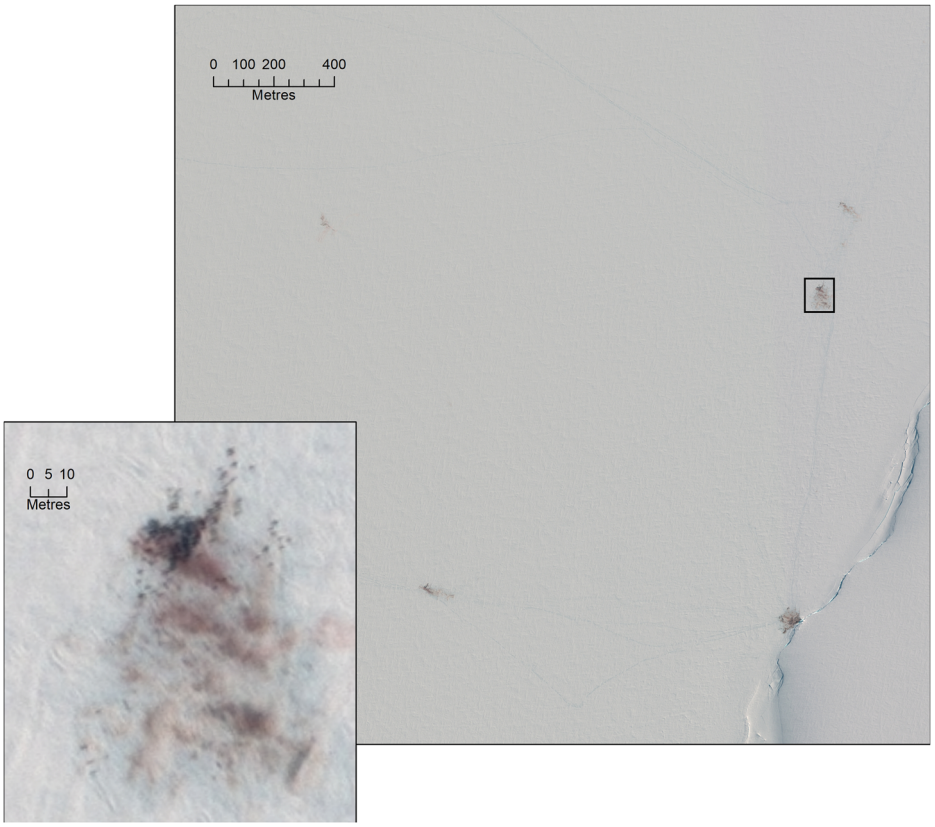

Fig. 4 | Example of VHR imagery of moulting penguins. This is a small clip of the WorldView2 imagery used in this study. This image is from 5th Feb 2022, in the middle of the emperor penguins' moult period. The larger image shows five groups of emperor penguins on the fast ice near the coast of the Guest Peninsula. The inset is a zoom-in of one of the groups showing that in each group, some individual birds can be identified, but in many cases, the close grouping of the birds negates the possibility of individual counts at this resolution. The brown areas are from the bird's guano and show that the birds were at the location for some time, and can infer recent movements. In these groups, we can deduce that the birds have moved slightly, but only a few tens of metres during their moult.

optical satellite imagery were examined. The VHR imagery was Worldview2 data at 50 cm resolution (image IDs: 10300100CD5D38 (5th Feb 2022), 10300100F71C8B (11 Feb 2024), 10300100F4C8140 (11 Feb 2024) acquired from the image provider Vantor. These images were deemed the most suitable in the Vantor archive, which, in this remote region, is limited. In these images, penguins can be clearly seen as small black dots (Fig. 4), but often the close grouping of the moulting penguins merges the black dots together and precludes individual counting. The total area of the VHR images was 239 km^2. To estimate the area of penguins in these three images, we cropped around the penguin groups; a binary threshold was used to extract black pixels to enable a rough estimate of the area occupied by penguins. Seals can also be seen in the WorldView2 imagery, and can be counted individually with some confidence. They can easily be differentiated from penguins as they are typically 2–3 m in length and constitute many more pixels, opposed to a penguin, which is a maximum of 1 m long and covers a much smaller area.

Sentinel-2/Worldview2 comparison

By coincidence, one of the WorldView2 images was taken on the same day as a Sentinel-2 image (11th February 2024). Comparing these two synchronous images enabled us to quantitatively test the ability of Sentinel-2 to accurately identify moulting groups. The total overlap of the two images was limited to 45.5 km^2 but included enough groups for a comparative statistical analysis. To understand the veracity of the detections from Sentinel-2, we compared the number and locations of visually identified groups of moulting penguins in Sentinel-2 images (10 m spatial resolution), with synchronous Very High Resolution (50 cm resolution) WorldView2 imagery (Fig. 5). The VHR imagery provided high confidence that moulting birds can be differentiated from guano and often allows identification of individuals. Satellite imagery from each platform was downloaded and displayed in ArcGIS (version 10.6 ESRI 2025). Sentinel-2 imagery was visualized using a Standard Deviation stretch using the three-band combination (8/3/2). Each image was searched individually at a 1:10,000 scale. All areas of fast ice and pack ice in the synchronous imagery were searched for areas of brown pixels. Previous studies show that it is possible to detect emperor penguin breeding colonies using Sentinel-2[30,32] and in larger groups, the penguins can be distinguished from the guano. In the February images used in this study, this was also the case, although it was often not clear if the brown staining on the ice in February was the result of guano, dirty ice (from feathers or algae) or both. The location of each of the identified penguin groups was digitised first in Sentinel-2 and then separately in the Worldview2 image, and the positions were compared. Positions in the two images that were within 100 m were classified as a matching group of penguins. Results were compared using standard remote sensing metrics of precision, recall and F1 score.

Sentinel-2 search

We searched all available cloud-free Sentinel-2 imagery of the area of interest between 10th January and 11th March in the years 2019–2025 (see Supplemental Table 1 "Observations from individual years" for details). The visual search was conducted in the same way and at the same scale as the Sentinl-2/WorldView2 comparison. In some years and in some areas, persistent cloud cover restricted the full coverage of the areas so that a small percentage (~5-10%) of the search area was not covered by suitable imagery. In each year, a composite image was made from the available imagery, and where multiple possible images were available, the image closest to 1st February was utilised. In many cases, multiple images enabled tracking the small brown dots (penguin groups) over time, and in some cases, it was possible to document the arrival of moulting penguins, as well as the movement and dispersion of the groups. At first arrival, penguin groups in the Sentinel-2 imagery usually appeared as dark-grey pixels and were difficult to distinguish from other environmental features (such as wet ice or melt-pools), but as the moult progressed, the pixels around the penguins became "browner" either from guano or dirty ice. This brown colour is easier to discriminate from the surrounding ice than other features such as

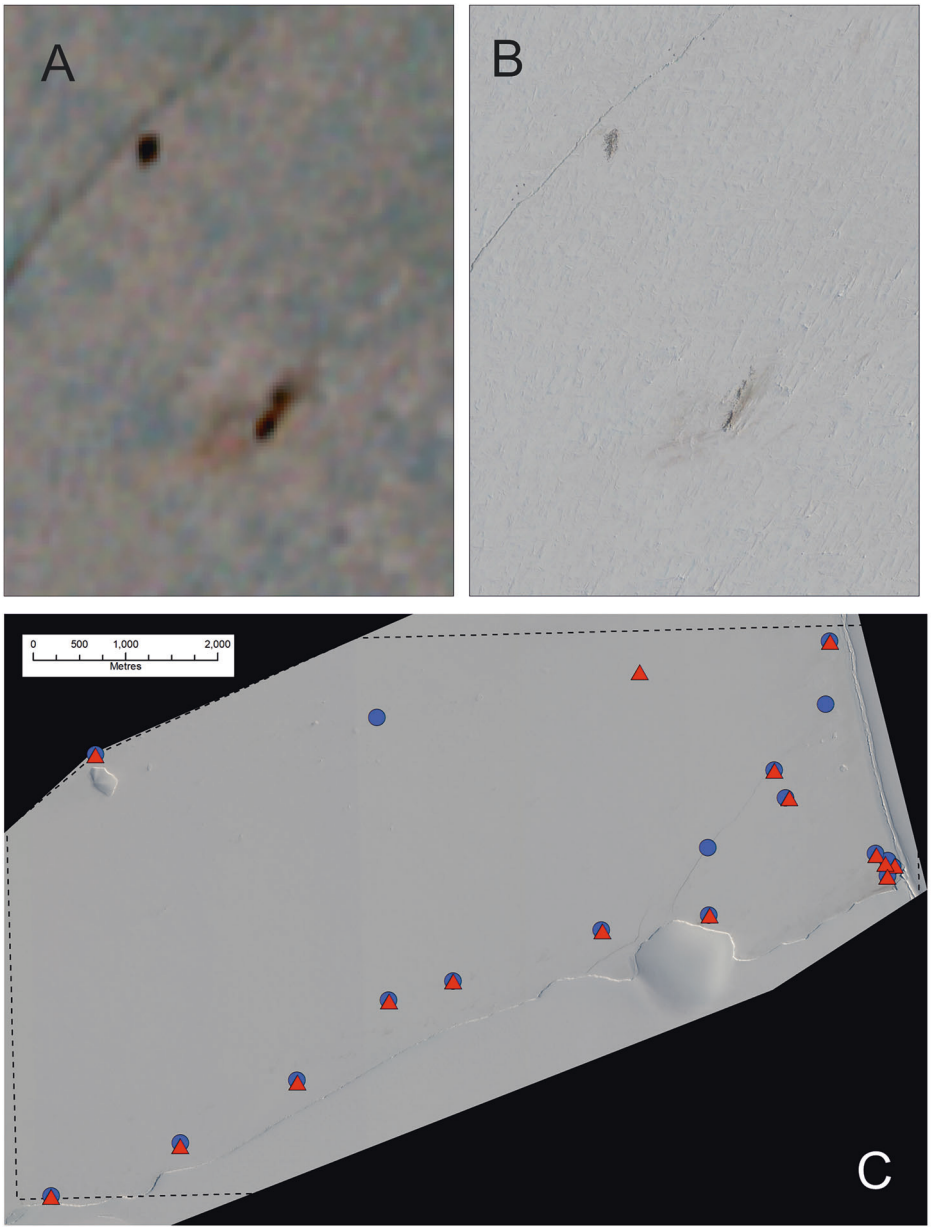

Fig. 5 | Comparison of Sentinel-2 and WorldView2 data from overlapping imagery taken on the same day (11th February 2024). A Shows an example of the brown patches as seen in Sentinel-2. **B** Shows how those same patches look on the same day in higher resolution WorldView2 data, confirming that these are groups of penguins. **C** Displays the results of the comparative Analysis; blue dots are groups of penguins identified in the WorldView2 imagery, and red triangles indicate groups of penguins identified in the Sentinel-2 imagery in a manual analysis. The dashed line indicates the area of synchronous overlapping imagery. The background image is from the Worldview2 image.

melt pools, cracks and shadow, and acts as a unique identifier for the penguin groups. The surrounding area of interest has no rock, which would be the only other possible brown area. Sometime in early March, the groups of penguins disappeared as they presumably left the area to return to the ocean.

Results

WorldView2 analysis

Satellite imagery has been routinely used for estimating emperor penguin numbers for over a decade[11,12,33,34]. In WorldView2 images, individual penguins could clearly be seen. The area of penguins classified by the binary threshold method in the three VHR images amounted to ~76,000 m^2 in the southern sector in 2022 and 4000 m^2 in the eastern image in 2024. This was the area of the penguins themselves, rather than their guano. These figures are approximate and probably a slight underestimate, as the binary classification sometimes missed isolated individual penguins that could be identified visually. Overestimation is also possible and can be caused by dense guano or low sun angle (excessive shadows), which this image did not have.

Sentinel-2/Worldview2 comparison results

In the 45.5 km^2 area for which synchronous satellite imagery was available, there were 16 brown patches in Sentinel-2 compared to 18 groups in the comparable WorldView2 imagery. Of these, 15 were in the same positions (Fig. 5). Statistically, these equate to a precision of 0.9375, a recall of 0.8333 and an F1 score of 0.8823. The three groups missed in the Sentinel-2 imagery were small aggregations of penguins, the largest of which was very close to a crack in the sea ice, which made identification difficult. The one false positive was a brown patch that may have been an area of old guano/feathers that penguins had probably previously occupied earlier in the season, and was misclassified in the Sentinel-2 data. Several other paler brown patches could also be seen, but these were not classified as penguins in either image. The results show that Sentinel-2 can be used effectively to search for moulting emperor penguins over a wide scale on fast ice and that the majority can be found in the freely available medium resolution imagery.

Sentinel-2 search results

Generally, brown clusters of pixels in Sentinel-2 imagery could be clearly seen over the search area in all years (2019–2025). They often extended over

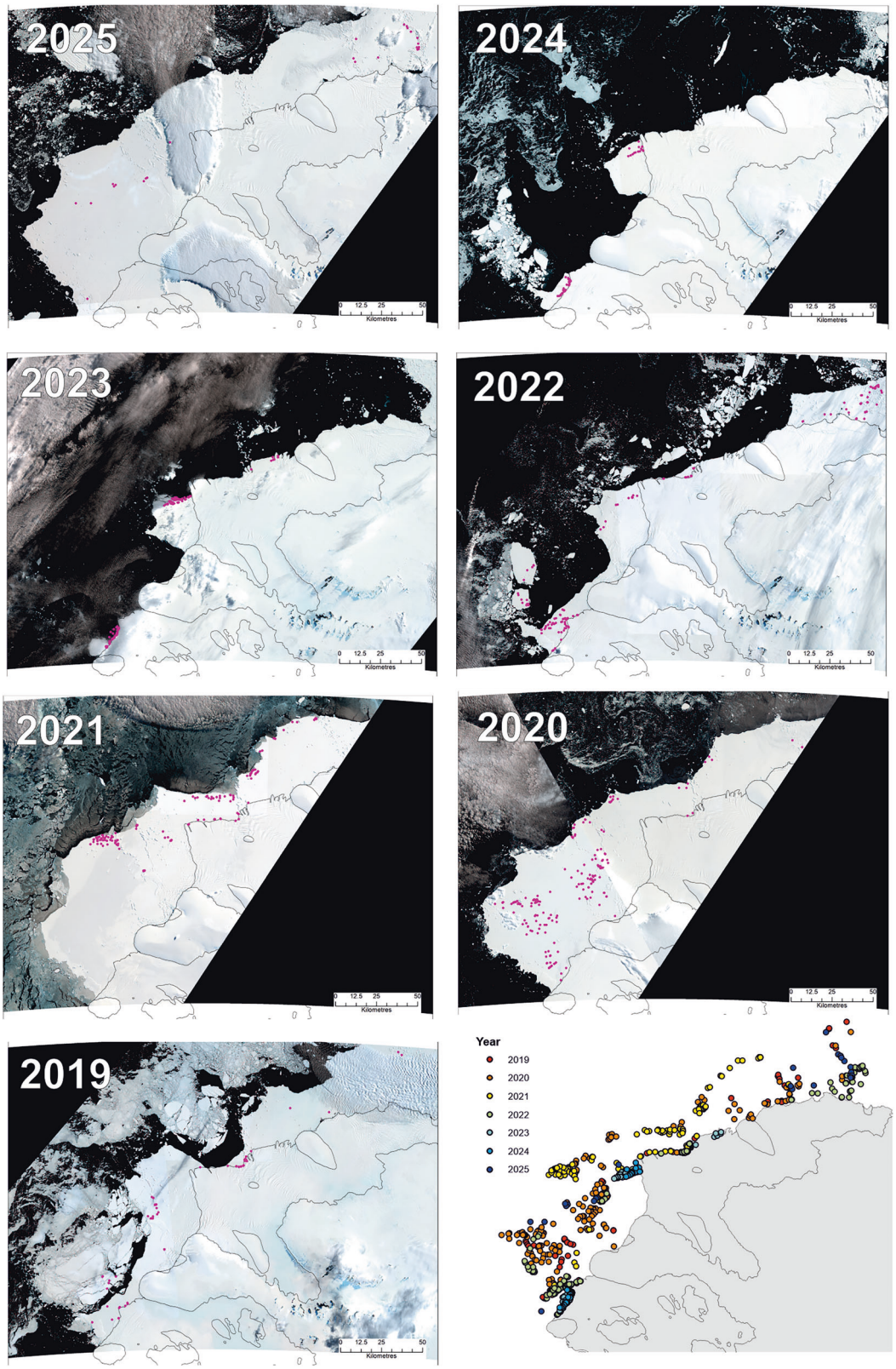

Fig. 6 | Results of the Sentinel-2 survey. Pink dots represent identified moulting groups over seven years of Sentinel-2 imagery from 2019 to 2025. The underlying imagery in each tile is a snapshot of the ice conditions in each year, although the timing varies. Dates of underlying imagery are: 15 Feb 2025, 11 Feb 2024, 3 Feb 2023, 5 Feb 2022, 11 March 2021, 15th and 25 Feb 2020 combined, 1st Feb 2019 (note that these were not the only images used to find moulting groups). The bottom right panel shows the combined annual points, colour-coded by year.

Table 1 | Maximal number of penguin groups identified per year in Sentinel-2 imagery

Year	Total groups	Area 1	Area 2	Area 3	Area 4	Fast ice minima km²
2019	96	32	21	24	19	6500
2020	224	93	87	9	35	10,600
2021	132	7	60	54	11	11,200
2022	141	71	15	16	39	0
2023	247	143	96	8	0	0
2024	62	44	18	0	0	0
2025	25	1	9	0	15	8000
Mean	132	56	44	16	17	5186

Areas are: 1. Vollmer Island to Guest Peninsula; 2. Guest Peninsula to Block Bay; 3. Block Bay to Newman Island; 4. Newman Island to Groves Island (see main text and Fig. 3 for more detail). The fast ice minimum relates to the coverage of fast ice in late February or early March, depending upon the availability of cloud-free satellite imagery (Supplemental 2).

the whole area of interest, but were almost always located on land-fast sea ice. The only time that groups of penguins were seen in pack ice was in 2022 and 2019, when several groups ($n = 14$ in 2022 and $n = 6$ in 2019) were located on fast ice that broke up in late January. On both occasions, the ice floes stayed near their original location for 1–2 weeks after breakup, and penguin groups could be seen on the pack ice. However, by mid-February in 2022 and late February in 2019, these ice floes had disintegrated, and penguins could no longer be seen in the pack ice.

Over the seven study years, the position, distribution pattern, number of groups, and timing of the moult varied (Fig. 6 and Table 1). The main driver of the penguin distribution was the sea ice extent. In years with low sea ice, especially in 2019, 2022, 2023 and 2024, the distribution and the position of the penguin groups was generally constrained by areas of fast ice near the coast (Fig. 6). In these years the groups were more concentrated (mean distance apart in 2023 =231 m, compared to 2019 = 1690 m) and the size of the clusters tended to be larger. Some groups probably contained several thousand individuals. In these low sea ice years, the groups were often clustered near the coast, probably because of the more stable, or longer-lasting nature of the ice there. In some instances, they had moved into rifts in the ice shelf or up onto the ice shelf. In years with more extensive sea ice, the pattern was more varied, and groups were generally smaller and more widely distributed (for more details of individual years, see Supplemental Table 1 "Observations from individual years").

In 2020, the penguin groups ($n = 224$) were distributed across the fast ice, which at that time was extensive throughout the season (Fig. 6 and Supplemental Table 1 "Observations from individual years") with a width of up to 80 km and an area of over 10,000 km^2. But one year later, although the ice conditions were similar, most groups ($n = 95$ of 132) were within 5–10 km of the sea ice-edge. However, the 2021 image was taken on 11 March at a time when most of the groups were departing, which may be why they were at the ice edge. In comparison, in 2020, by 16 March, all moulting groups had left, and there was no sign of any penguins on the ice. This pattern was typical: groups gathered throughout January, reached a peak in early February and departed in early March.

Numbers of moulting groups varied (Table 1); the largest number was identified in 2023 when 247 groups were recorded. The lowest number of groups ($n = 25$) was recorded in 2025. All groups sighted in 2025 were small, just a few pixels, and the majority occurred further east on extensive fast ice off the Land Glacier (75.25° S, 142.50° W), north of Grant Island. This area was also occasionally used in other years, particularly in 2022. However, only in 2025 were most of the groups found in the area.

The penguin groups mainly concentrated in four distinct areas of fast ice: 1. between Vollmer Island (76.7° S, 150.7° W), and the western part of Guest Peninsula (76.4° S, 149.7° W): 2. between the western edge of the Guest Peninsula (76.4° S, 149.7° W) and the northwestern point of the ice shelf in Block Bay surrounding Driscol Island (75.75° S, 148.5° W): 3. the northwestern point of the ice shelf surrounding Driscol Island and Newman Island (75.5° S, 146.1° W) (including Stephen Island), and 4: the area between Newman Island (75.5° S, 146.1° W) and the ice coast between Newman Island and Groves Island (75.35° S, 143.0° W) (Table 1).

In 2022, the fast ice extent in the region was low, and by 23rd Feb, only one patch of less than 1000 km^2 remained (Table 1). In 2023 and 2024, all fast ice broke out during the moulting period throughout the area. In 2023, this happened between 30 January and 2 February, and in 2024, around 9 February. In both instances, penguin groups were on the fast when it broke up. In 2023, almost all pack ice disintegrated into bergy bits and brash and open water within the next week. In 2024, the eastern pack ice area disintegrated, but in the west of the area, the fast ice broke into pack ice, which persisted until the end of February. In both years, by the end of February, no fast ice existed along this stretch of coastline west of the Land Glacier.

Discussion

This is the first time that the moult locations of the emperor penguins' annual cycle have been identified and tracked using satellite imagery. The ability to confidently discriminate moulting groups on sea ice, using both VHR and medium resolution imagery, will greatly improve our knowledge of this crucial and little-studied period of the life history of emperor penguins. This study focuses on one geographic region, where most birds from the Ross Sea region are likely to moult. Whether emperor penguins in other geographic regions can be seen in similar imagery is not yet known. This may depend upon whether aggregations large enough to be visible in satellite imagery form in other areas, which in turn may depend upon the size of the local population and the area of available ice. Smaller groups, of just a few tens, will still be visible in VHR satellites, but may not be visible in Sentinel-2

It is almost certain that the penguins seen here are emperor penguins, as there are only two species of penguin that moult on the sea ice. Adélie penguins do not start moult until March.[32] It is not yet known whether the same methods are applicable to Adélie penguins. What is also clear is that in this region, emperor penguins moult on fast ice, not pack ice, although they are occasionally seen on ice floes when the fast ice breaks up. The birds aggregate in groups that range in size from approximately 20-50 individuals, but occasionally much larger groups form, often hundreds strong. This happens more frequently when there is less fast ice. In years when sea ice extent was low, groups tended to be larger, many groups occupying over 100 m^2 in area; the largest being over 1200 m^2. Although it is not possible to count individual penguins in the 50 cm imagery used here, it may be possible in 30 cm imagery that is currently available to task.

The large number of groups seen each year in the Sentinel-2 imagery and the area of penguins derived from the WorldView2 data suggest that most of the Ross Sea population moults in this area. It is tempting to compare the area of penguins estimated from the WorldView2 analysis with the published areas and densities from the previous satellite studies. These return densities of approximately 1 penguin per square metre[11]. If these same densities were applied to our areas assessed in the 2022 VHR image, it would equate to 76,000 adult penguins. This image contains only 65 out of the 141 penguin groups counted in Sentinel-2 imagery that year (46%). But comparison of density estimates from the breeding season to the moulting season should be done with caution, as those density estimates are from the spring, when only a portion of the adults are present, and an unknown number of chicks are also in the classification. In our imagery, the moult will comprise all adults (male and female), and may include juveniles and subadults over one year old. Therefore, there is probably limited comparability between the spring penguin densities where we have ground truthing and the densities seen here. Future aerial or UAV survey over the moulting area may enable more robust density estimates, but higher resolution satellite imagery that facilitates individual counts would provide more reliable estimates. Even though the area of penguins assessed in the VHR imagery was considerable, the area of available VHR imagery only covered a small part of the total area where penguins were identified.

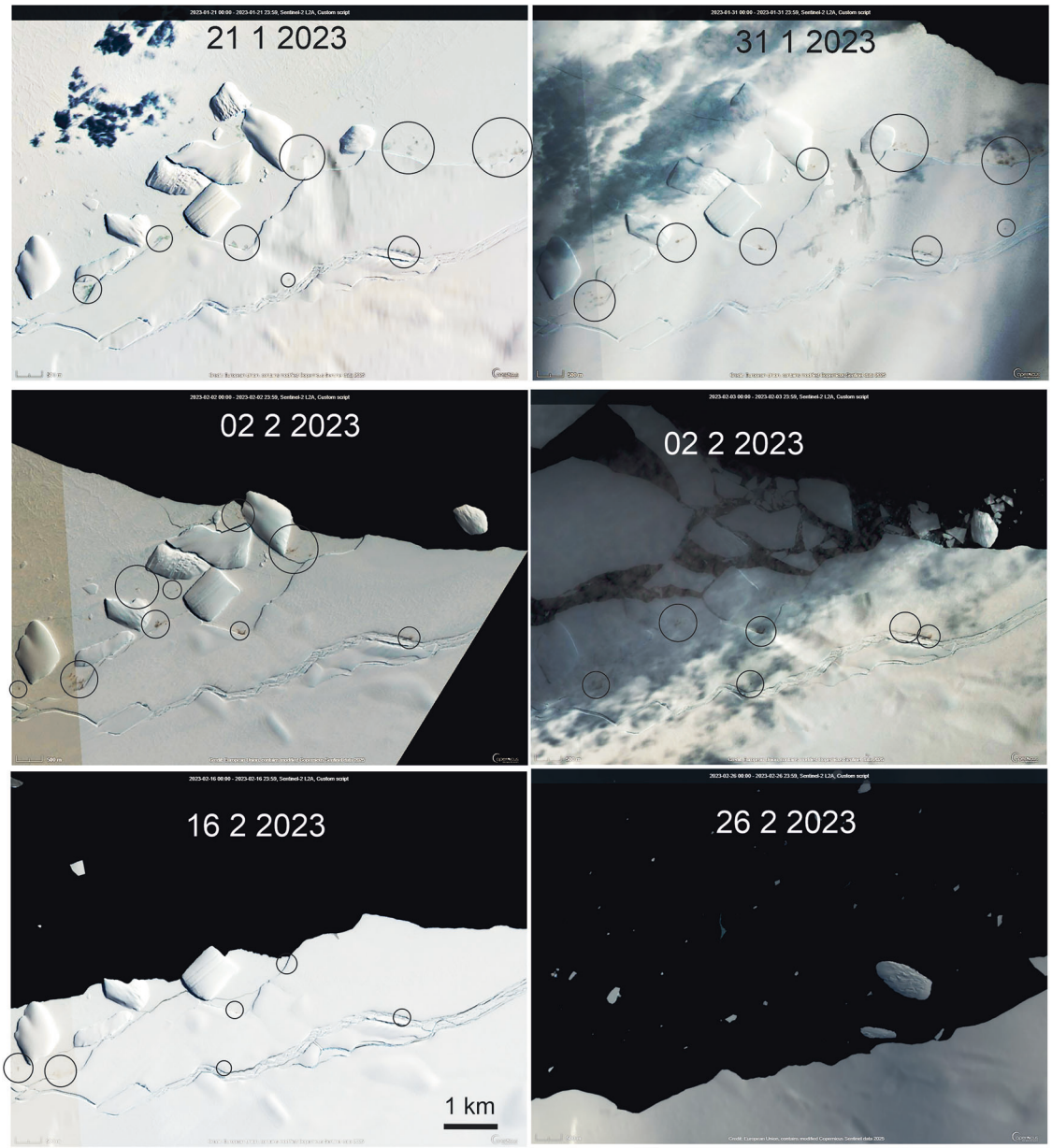

Fig. 7 | Six Sentinel-2 satellite images of a small area of the coast near the Guest Peninsula between late January and late February 2023, showing the breakout of fast ice where the emperor penguins were moulting. The moulting groups can just be seen in these images (which are not displayed at full resolution), and to help the viewer, we have highlighted the locations of moulting groups with black circles. The sequences show the breakup of the fast ice where the penguins are located. In this example, several groups went onto the ice shelf or into an ice chasm away from the coast to try to avoid early breakup, but this small piece of shelf also broke out, putting the penguins at risk.

The time series of Sentinel-2 imagery shows that low sea ice extent and early fast ice breakup in 2022, 2023 and 2024 affected the moulting penguins. In 2022 the majority of penguins were affected by early ice break up While in 2023 and 2024 all, or almost all penguins experienced ice breaking up (Fig. 7). As the ice disintegrated into brash and open water, these penguins may have become immersed when only partially through their moult (more information on the sea ice conditions and emperor penguin groups from individual years can be found in Supplemental Table 1 "Observations from individual years"). The implications of this are as yet unclear. It has been hypothesised that the moulting period is the time of highest adult mortality, as penguins do not survive the moult if they have not accumulated sufficient body reserves to undergo this highly energy-intensive process[18]. Future population studies at colonies in the Ross Sea corresponding to this moulting study may shed light on the link between moulting and breeding populations.

Another interesting observation is that after two seasons of poor sea ice conditions and early ice break-up in 2023 and 2024, very few groups of penguins were seen in the region in 2025. In 2023, 247 penguin groups were identified, but after the early ice break-up that year, this dropped to 67 in 2024, and after another year of early break-up, the numbers dropped again. In 2025, only 25 very small groups could be identified, although there were extensive areas of apparently suitable ice. In 2025, the ice was much more extensive, but although the ice had returned, many of the penguins did not. Where the penguins that did not return went to moult is unknown. Some of the few groups that were seen went further eastwards towards a more stable area of fast ice around Groves Island and the terminus of the Land Glacier 150 km further east (Fig. 6), and would have added considerable distance to the pre-moulting and post-moulting journey. This may impact the time when adults return to the colonies in the Ross Sea, some of which are already over 1000 km away.

Seals are also clearly visible in the VHR satellite imagery and were counted manually (280 in the 2022 image in the south and 849 in the 2024 image further north). Generally, they occurred close to the coast near cracks in the fast ice. As the VHR imagery only covered a small portion of the coastline (~50 km), it is likely that many others also utilise these areas of multiyear fast ice. It is assumed that these seals are moulting. Although it remains difficult to ascertain which species they belong to, it is likely that they were Ross and/or Weddell seals, two species that frequent this region[35]. The large number and close aggregation indicate that this area is an important and previously unknown moulting area for pinnipeds (Supplemental Table 2 "Seals").

Conclusion

Overall, this paper is a preliminary study that documents the potential of using satellite images to identify emperor penguins and other marine predators during their moult and track their locations and movements at a critical time in their life history.

The use of satellite imagery can improve our understanding of several aspects of species:

1. Satellites can reliably be used to detect moulting emperor penguins.
2. The emperor penguins from the Ross Sea moult on fast ice and often gather in large numbers, sometimes close to each other.
3. In six out of seven years, a significant proportion, possibly the majority, of these emperor penguins moulted in a certain region of fast ice off the Marie Byrd Land coast.
4. The reduction of sea ice off the Marie Byrd Land coast in recent years may have had a serious impact on the moulting birds.

These new observations also lead to new questions that need to be addressed. Potentially, the most critical question will be what is the potential impact of changes in moult habitat on the size of breeding populations in the Ross Sea? Other ongoing studies are assessing up-to-date population changes in the region, which may help answer this question. Additionally, future research should assess what happened to the regional moulting population in 2025 and why it did not return to the study area. Finally, the question of how far this method can be successfully applied to other regions should also be addressed to assess the impact of extreme low sea ice extent and duration, as this environmental phenomenon is now impacting large parts of the continental coastline.

Data availability

Sentinel_2 satellite data is freely available from the Copernicus Browser: https://browser.dataspace.copernicus.eu. Images used in this study are listed in Supplemental Table 1 *sentinel2 images available*. Point data from the annual seven-year study is available as csv files in Supplemental Table 2 *locations of penguin groups*.

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Author contributions

P.T. Fretwell: project design, collection of data, analysis of data, writing of paper.

Competing interests

The author declares no competing interests.

Additional information

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